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THE SUMMER COOL CHANGE OF SOUTH-EASTERN AUSTRALIA

I. GENERAL BEHAVIOUR

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THE SUMMER COOL CHANGE OF SOUTH-EASTERN AUSTRALIA

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Summary

The frequency, movement, and certain structural features of fronts and front-like disturbances are studied by some 50 detailed analyses, aided by special observations of passages, during the seasons of 1953–54 and 1954–55. They are investigated separately according to whether a single or two successive discontinuities occur.

It is shown that, excepting the trailing change, a marked diurnal variation of frequency of passage can be attributed to a diurnal variation in speed of movement. This is shown to be related to the similar variation of the horizontal pressure field caused by the daily cycle of differential heating between land and sea.

Single and complex (double) changes seem to be distinguished also in the surface convergence and shear associated with the transition zone between warm and cold air, the overall thermal contrasts in the lower troposphere, and characteristics of the upper flow.

Evidence is presented that quite frequently a disturbance, particularly the leading surface discontinuity of a complex, is non-frontal in origin, and may be readily attributed to the effects of the associated pressure jump. Data are given to show that the incursion of a coastal front also induces a change either singly or ahead of a cold front. The various hypotheses concerning the double cool change are reviewed in the light of the present data.

I. Introduction

It has long been recognized that the west-east orientation of the southern Australian coastline produces, particularly during the summer, contrasts of a magnitude such as to profoundly affect periodic and aperiodic variations in meteorological elements. The vast expanses of ocean to poleward locally accentuate the temperature contrasts due to differential heating which are generally found in the relevant latitude belt of the southern hemisphere. Thus Meinardus (1940) and Loewe (1948) gave evidence for a hemispheric-wide extent of a maximum *interdiurnal* variability in various elements in latitudes 35–40°, during the summer. The distribution of *diurnal* variation of pressure (Commonwealth Bureau of Meteorology 1937, 1949) and of temperature over and around the Australian continent also brings out the strong contrasts in the coastal regions and the immediate hinterland; and, if the coastal intensification of the associated fluctuating horizontal gradients of pressure and temperature were to affect those (*per se*) aperiodic changes which are controlled by the sequences of large-scale on-shore and off-shore air currents, the behaviour of summer weather changes would depend on it to a large extent.

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A systematic study of the nature and behaviour of the typical "cool changes", which is the popular name given in the region to the cold fronts and cold-front–like travelling disturbances of the summer season, is therefore desirable, especially since it may, if only indirectly, be useful in improving their prediction. Forecasting of the arrival of these usually sudden changes with some degree of precision is of considerable economic importance in the region. Bushfire control and short-term planning operations in the primary and catering industries may be mentioned here as examples of activities concerned with improvement of the day-to-day prediction standard.

This paper describes an investigation which has been conducted in the Division of Meteorological Physics during the summers 1953–54 and 1954–55 (and continued subsequently) with the object, firstly, of obtaining more detailed information on the nature and behaviour of cool changes and secondly, of attempting to solve some of the problems which they present. With the cooperation of private volunteer observers and of the officers of several Government organizations,* data were obtained to render possible a semi-statistical representation of salient features at the surface over a fairly wide region. Owing to the paucity of routine aerological observations and the failure to obtain more frequently special observations from the upper air, the three-dimensional representation has been restricted in scope and area. On some occasions it was, however, possible to study structure, medium-scale circulation, and physical processes associated with the sloping zones of concentrated wind shear from special upper wind measurements and from autographic records. The results of the study of such data, particularly of those obtained from a close network of stations set up specifically for this purpose in a wide region centred upon Mt. Gambier during part of the third season, will be communicated in Part II and elsewhere.

II. The General Problem

The dominant sequence of alternating streams carrying warm air masses seaward and cold masses landward and inland is broadly depicted by the migrating anticyclones with centres off the coast and trough-like extensions from intervening depressions. The flow patterns, frequently modified by a well-defined col between the anticyclones, favour maintenance and genesis of zones of sharp contrast in temperature and humidity which are usually translated at some stage north- and eastward, traversing the coastal regions and the hinterland as cool changes. For the purposes of the present paper, the term "front" will be avoided as much as possible so as to leave open the physical nature of the travelling discontinuities at the surface. The term "change", unless qualified, is used to describe a sequence of events rather than a single discontinuity and may include two, or more, discontinuities which give the appearance of fronts, and occur within a few hours of one another. The counterpart to these changes, which would be associated with a discontinuity having warm-front character, is extremely rare in summer; this is also reflected in a marked skewness in the frequency distribution of interdiurnal temperature changes, a relatively high frequency of moderate rises being accompanied by a relatively low frequency of sharper falls (Loewe 1948).

* These observers and organizations are listed in Appendix II.

The method in practice at the present time of predicting the arrival of cool changes is essentially based on projecting the change-line or lines which are located in variable sectors of the surface large-scale trough, with the relevant velocity of the wind behind them, and with adjustments indicated by experience. Although efforts have been made to find a workable model of the circulation in the region, there is a suggestion of a tendency for the changes to arrive earlier than predicted. Check calculations suggested a skewness in the frequency distribution of timing errors; and, as long as errors of this kind cannot be grouped according to more definite classes with distinctly different mechanisms, progress in prediction will be slow.

Two aspects in the behaviour of changes merit closer study in this connexion. One is non-uniform distribution of arrival at a locality over the day (24 hr). Studies by Hunt (1894), "Observer" (1944), Forder (1945), and Loewe (1945), gave evidence of a preference for passages in the afternoon at many places in the region, and of a second less pronounced frequency maximum at other times of the day at some stations. Various possible reasons for the distribution at Melbourne were suggested by Loewe, such as the influence of the diurnal and semi-diurnal pressure oscillations on frontal movement, the effects of heating over the land, and a diurnal variation of speed of movement, but there was little evidence in the limited data to support any of these hypotheses.

Variations with time of day of the passage of cold fronts and of changes with cold-front character have been recently investigated by Köster (1955) using records from Frankfurt. Pursuing the earlier studies by British and German writers, this author gave some evidence of the effects of a diurnal cycle of convective mixing and ensuing release of instability for summer cold fronts, and of the semi-diurnal pressure wave on weaker changes with cold-front character in general.

The other important problem concerns the "doubling up" of the discontinuity in the surface fields of temperature, wind, and humidity, which occurs with a quite large proportion of changes. In the Australian region the phenomenon, although well known, has as yet not been studied systematically. It is not limited to the warm season. Overseas literature dealing explicitly or implicitly with the double change is considerable. Although there exist, especially in the United States of America, workable hypotheses and quantitative theories on the genesis of prefrontal squall lines and similar disturbances, the general atmospheric conditions in the regions over which these were studied in detail are very different from those prevailing in the region here under consideration.

Among various Australian hypotheses and ideas regarding the double change, not one has found general acceptance. Forder (1945) attempted to explain two distinct steps as passages of active cold fronts between warm continental or tropical maritime, cool southern Indian Ocean air and cold air masses transported from higher latitudes in the "cold outbreak" which follows in the wake of a deep depression centred south of Tasmania. It would seem doubtful whether such outbreaks were of as frequent occurrence in summer as the observation of double changes. As the very rapid modification of air masses over the continent renders conventional air mass analysis virtually impracticable (Clarke 1954), this issue will not be pursued in the present publication.

The propulsion across the region of a col between successive anticyclones may be invoked to explain the formation of a frontal zone near the coast ("coastal front") in the baroclinic field along it. This process would frequently take place ahead of a major front associated with a depression in the main westerlies. Two chief regions of formation have been suggested; along the coast of Western Australia (Cassidy 1945*a*) and along the coasts of south-east South Australia and south-west Tasmania (Forder 1945). Extensive data have been furnished by Langford (1948, 1950) to show, among other things, that Cassidy's concept would require a highly improbable pressure distribution over the Great Australian Bight.

A model which bears a resemblance to the "polar trough" described by Riehl (1945) has been proposed by Gibbs (1945). This model makes provision for surface changes similar to those observed with weak fronts, and envisages a convergence zone preceding the main front. This zone at the surface would be the reflection of a trough in the upper westerly flow.

An interesting hypothesis, put forward in a later paper by Cassidy (1945*b*), embodies the following sequence of events: cold-front retardation; retrogression as warm front (aloft); "turning over" of lower portion (as result of rapid heating over land) and assuming thereby cold-frontal slope; system caught up in circulation ahead of approaching (major) cold front; advancing as leading discontinuity of a double change. Peculiarities observed in the cloud sequence with complex changes could be accounted for by such a process, but the "turning over" process appears physically improbable in view of the intense convective mixing over the land. Furthermore, temperature aloft is observed to fall rather than to rise with the advent of the early cloud system. This was emphasized by Clarke (1954), who gave evidence to support the idea that the trough associated with a cold front tends to shift into the rear of the front, which would gradually disappear in the frontolytic field ahead and be replaced by a new one in the trough. On the face of it, this mechanism would account for the occurrence of double changes (and also multiple changes which, incidentally, are noted at times), the leading step or steps being a front or a system of discontinuities, whereas the trailing step would be identical with the translated trough or front.

Finally, Ashton (1952), from considerations given by Godson (1951), suggested that the steps of a double change might in fact be the leading and trailing edges of a broad frontal zone. No arguments were advanced, however, to account for the frequently abrupt changes (discontinuities) in the various elements at the edges of the zone.

III. Average Appearance of "Changes" at Ground Level

(*a*) *Method of Representation*

The observational material and its collation are discussed in Appendix I. The representation of averages in this section must be considered merely an indication of well-founded climatological values, since they are mainly averages from two seasons only. They have been taken in two ways so as to bring out different aspects of the changes. One method has been to use information from the questionnaire returns sent in by voluntary observers (see Appendix I). In these, overnight

changes will be missing to some extent, while some of such phenomena as local storms, sea-breezes, and katabatic winds will figure, notwithstanding the request to report them separately or not at all.

The second method has been to consider only changes which have been analysed as affecting most of the region in question and to use in addition Commonwealth Bureau of Meteorology routine reports and other information listed in Appendix I. This approach has the advantages of eliminating spurious changes, of including the effect of disturbances which may have affected some areas only weakly so as to escape the vigil of voluntary observers, and of including overnight changes in roughly the correct proportion.

The statistics according to these two methods are set out in the upper and lower portion of Table 1. Five "key stations", four of which are aerodromes maintaining autographic instruments, were selected so as to give a coverage of the area. Unfortunately, no questionnaires were sent to aviation stations in South Australia. The proximity of Wodonga, Rutherglen, and Beechworth (Wodonga group) made it possible to treat the returns from the three places as a single group, and the absence of autographic records there was thus compensated for to some extent. To give an indication of occurrences at a prominently oceanic station in roughly the same latitude as the region examined, averages were derived for Amsterdam Island (38° S., 77° E.) from 3-hourly synoptic reports. The table contains also regional means deduced from all available questionnaire returns, including those from the key stations, by judicious averaging.

The location of stations and delineation of regions is shown in Figure 12 accompanying Appendix I. East coast and northern Tasmania values are the least reliable, as there were few reporting stations and the observations extended there over only one season.

For most of the statistics in Table 1 each step of a double change—the steps being henceforth referred to as leading and trailing change (of a complex), for want of a better terminology—is considered as a separate event, but the values for interdiurnal variation are necessarily based on taking complex changes as a single event.

With a view to emphasizing differences between one region and another (including among them South Australia) and between single and complex changes, 12 rather well-marked changes of each class were selected from the analysed cases. Average winds before and after passage, temperature falls, and dew-point changes from 3-hourly reports from Meteorological Bureau Stations, are shown in Figure 10.

(*b*) *Discussion*

The averages in Table 1 and Figure 10 are not consistent in all respects. It is nevertheless possible to make from them certain generalizations as to the manner in which cool changes affect the area.

(i) *Frequencies.*—When the individual steps of complex changes are considered independently, there is a considerable variation of frequency over the region, with the highest values at the coast and a slight decrease eastward along the Victorian coast and a more marked decrease inland.

TABLE 1

AVERAGES OF QUANTITIES (AS INDICATED) RELATED TO COOL CHANGES, AT "KEY STATIONS" AND IN DISTRICTS

Source*	Quantity	Units	"Change"	Key Station						District							
				Mt. Gambier	Mildura	Essendon	East Sale	Wodonga Region	Amsterdam I.†	S.-W. Coastal	S.W.	N.W.	S. Central	N.E.	Gippsld.	E. Coast	N. Tas.
Q	Monthly frequency	—	Not specified	9·6	3·6	7·3	5·0	7·9	9·3	9	9	8	9	11	7	12	6
Q	Monthly frequency	—	Single	3·8	3·4	3·9	3·4	3·5	2·9	5	5	5	6	8	4	6	2
Q	Monthly frequency	—	Complex	2·9	0·2	1·7	0·8	2·2	3·2	2	2	2	2	2	2	3	2
BM	Percentage frequency	%	Dry	46	56	70	74	66	38	43	53	57	63	69	53	61	67
BM	Proportion with 24-hr rainfall ⩾ 0·05 in.	—	Wet	26/67	21/36	25/56	14/42	21/36	11/51								
BM	24-hr rainfall (⩾ 0·05 in.)	in.	Wet	0·37	0·34	0·49	0·41	0·54	—								
Q	Temperature fall—																
	With passage	°F	Not specified	3·7	7·6	5·9	6·4	7·6	3·0	6	9	7	8	7	7	8	4
	9 a.m.–9 a.m.	°F	Not specified	4·8	8·4	7·8	4·7	3·8	—								
BM	Dew-point change 9 a.m.–9 a.m.	°F	Not specified	—1·3	+0·1	—2·8	—4·0	—2·1	—								
BM	Percentage frequency	%	Accompanied by pressure jump	35	60	46	29	—	—								
BM	Percentage	%	Dry among changes with pressure jump	67	44	38	70	—	—								
A	Number of change-lines	—	Not specified	54	49	59	50	35	—								
AQ	Percentage	%	Not recorded in Q	30	59	29	46	37	—								
AQ	Percentage	%	Reported earlier or later	15	8	7	4	—	—								
A	Complex (double) changes: Time between steps	hr	Complex	6·0	—	4·3	3·3	3·7	6·2	4½	11	—	6	6½	4	7½	4½
Q	Temp. fall with passage	°F	Leading	4·0	—	5·7	5·0	0·0	0·0								
Q	Temp. fall with passage	°F	Trailing	2·5	—	5·3	6·0	6·0	1·8								
BM	Temp. fall 9 a.m.–9 a.m.	°F	Complex	7·8	7·8	9·1	6·2	5·4	—								
BM	Dew-point change 9 a.m.–9 a.m.	°F	Complex	—1·4	—0·5	—2·2	—4·7	—3·9	—								
Q	Backing of wind	°Azim.	Leading	55	—	95	110	52	64								
Q	Backing of wind	°Azim.	Trailing	40	—	85	50	70	43								
Q	Veer between steps	°Azim.	Complex	10	—	60	30	0	0								

* Q, questionnaire reports; A, analyses in Division of Meteorological Physics; BM, Commonwealth Bureau of Meteorology data.

† Data for this station from 3-hourly synoptic reports only.

(ii) *Temperature Fall.*—Averages show a slight increase eastward, and there is a suggestion of an initial increase followed by a slow decrease as distance from the coast is increased. The high values at Mildura are largely due to a high proportion of changes passing that region during the early evening when diurnal (radiative) cooling is most rapid. In northern Tasmania—as also at Amsterdam Island—the falls are considerably smaller than elsewhere, and this may be ascribed to the air in the pre-change north-westerlies being cooled over the cool waters of Bass Strait. This modification of the warm air and the orography of the region frequently render difficult the detection of passages there (see network of recording instruments, Figure 11 in Appendix I).

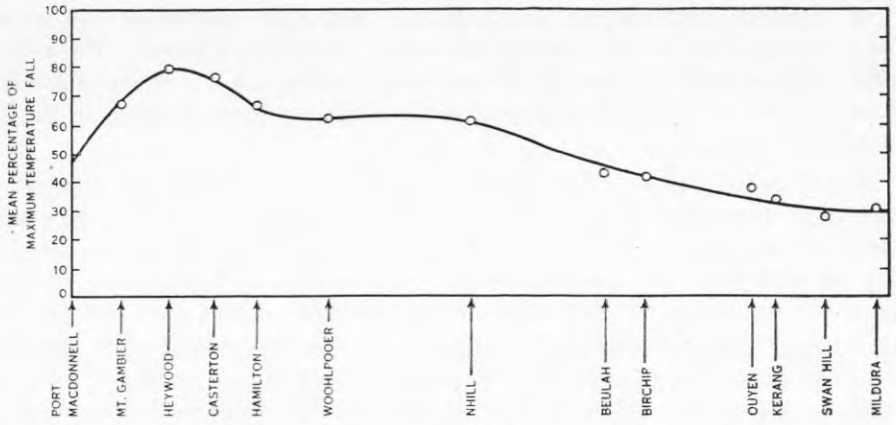

Fig. 1.—Decrease of maximum temperature with cool changes in western Victoria. Average percentage of largest fall on each occasion for 15 dry changes.

The variation in cooling as the change-lines move inland is represented in a different manner in Figure 1. The interdiurnal decrease in maximum temperature averaged for 15 dry changes is plotted against distance along a line indicated by the stations, the cooling in each case being expressed as percentage of the strongest cooling along the line. The gradual decrease of temperature fall at larger distances inland is readily ascribed to over-land modification of the cool air by surface heating, whereas the slighter falls evident near the coast are not consistent with prevailing pre-change off-shore winds. However, they may well be an effect of sea-breezes on the day *before* the arrival of the change. Strong off-shore winds would delay the arrival of the sea-breeze at the coast and diminish the speed and extent of penetration so much so that Mt. Gambier, more than 20 miles inland, would record high maxima occurring prior to the onset of the sea-breeze. As against this it may be stated that such winds are not as a rule established until the day of the large-scale cool change.

(iii) *Humidity Changes.*—The interdiurnal variation of dew-point is slight, on the average. The falls tend to increase eastward, presumably owing to the effect of entrainment of moist tropical air from a north-easterly direction on occasions, and there is a decrease inland showing the effect of evaporation in the initially (absolutely)

drier, cool air. Elimination of occasions with 24-hr rise (i.e. consideration of stronger changes) was found to increase the magnitude of the dew-point drop at all places, but not to alter the general pattern.

(iv) *Wind Shift.*—A fairly uniform pattern occurs over the area, except for complications in the east, presumably due to orography. The average backing is from 40 to 90°, but it was found that the angle between the most frequent preceding and following wind directions is nearly everywhere larger than the average backing. This is a reflection of a bimodal distribution of directions which in turn is, at least partly, a reflection of the occurrence of complex (double) changes. Wind velocities generally show a slight increase, though in south central Victoria there is frequently a small decrease.

(v) *Rainfall.*—Rather less than half the changes are associated with precipitation, the proportion of dry changes increasing eastward and inland. The average rainfall recorded with wet changes is surprisingly uniform, but a study of the data (not reproduced) indicated that large falls are relatively more frequent in the east than in the west.

(vi) *Pressure Change.*—The high proportion of cool changes accompanied by abrupt rises of pressure (row 11, Table 1) is noteworthy, especially as in a small minority of cases the rise is followed by a fall shortly afterwards, which gives the typical pressure variation associated with a heavy shower or thunderstorm. Furthermore, with an even higher proportion of changes with abrupt rises (jumps) there is no accompanying precipitation, mostly not even in the vicinity of the recorded jump. The proportion of changes with pressure jump is greater inland than near the coast. A possible relation of these locally recorded pressure discontinuities to the pressure-jump lines of the Freeman-Tepper type (see Tepper 1950) will be discussed in Part II.

(vii) *Single and Complex Changes.*—The variability of the frequency, especially the suggestion of a decrease eastward and inland of complex changes, might be due to the weakening and disappearance of the leading change, or the trailing change, or both as they advance. Some light will be shed on this phenomenon by considering the variation of frequency, speed of movement, and acceleration of change-lines with time of day (see Section IV).

It is seen from Table 1 and Figure 10 that the temperature fall with the leading change of a complex change tends to be larger than with the trailing change over most of the region. The dew-point usually rises temporarily with the first, and falls with the second step, and continues to fall for some hours after the passage of the latter; the wind backs and decreases with the leading change, and backs, in the average less sharply, and increases with the trailing change. At a number of places there is a veer of wind between passages, quite marked at some of them.

The frequent occurrence of double changes at Amsterdam Island is noteworthy, as it indicates the widespread nature of the phenomenon. At Stanley (northern Tasmania)—as also at Amsterdam Island—the rise of dew-point with the leading change is not observed. These places have in common that the warmest air, ahead of the leading change, must necessarily have an over-water trajectory. But King Island and Kangaroo Island with shorter over-water trajectories than Stanley do

show dew-point rises. As the wind at Gabo Island ahead of the leading change is from due north (on the average), the air there too must have had a preferred long trajectory over water with a comparatively high surface temperature. The fall of dew-point at Gabo Island exceeds that at Amsterdam Island. Wilson's Promontory, however, does not fall into the pattern.

Single changes and the leading steps of complexes appear to exhibit some similarity. The backing of wind is larger with the former, though not as large as the overall backing for complexes, and the initial direction is more westerly. The temperature fall does not much exceed that of the steps of a complex, but there is an initial rise of dew-point with single changes, chiefly in the western regions, and it is outstandingly large at some places in South Australia. This bears upon the trajectories of the cool air behind single changes rather than upon the origin of the warm air ahead, which streams from west-north-west rather than from north-west and so does not come from the desiccated regions in the interior of the continent. Further light will be thrown on these changes through an appraisal of large-scale pressure patterns associated with the cool changes (Section V(*a*)).

The rate of movement across the area and the orientation (in degrees west of north) of the change-lines were found to vary considerably from case to case and with individual changes from one region to another. A skew distribution emerged for the frequency of the time taken to traverse the area, the most frequent time being less than the mean. The skewness is much less pronounced for trailing changes of complexes than for leading changes or for single changes. Average values for orientation, speed, and ratios signifying acceleration of change-lines are given in the fifth column of Table 2 which sets out the diurnal variation of the various quantities (Section IV(*a*)). It is seen that single changes move more rapidly than complexes and that the leading change pertaining to this class moves faster than the trailing. The average angles of orientation indicate that the trailing change is rotated slightly counter-clockwise from the leading change, also a rather large departure of single changes from a meridional orientation is evident.

The figures in Table 2 for ratios of speed of change-lines indicate that they are accelerated in their movement from west to east, i.e. from Mt. Gambier to Gabo Island. This seems to be the case with other than trailing changes, single changes being speeded up most. The frequency of occurrence of ratios of different value (Table 3) shows that there is a bimodal distribution in leading changes of complexes, with a strong maximum of changes retarded as they move east and a smaller maximum of changes which are comparatively strongly accelerated. The trailing changes have a single maximum around unit ratio, emphasizing their comparative steadiness of movement, and the single changes have a relatively flat distribution. On the average, changes are slowing down on crossing the coast (ratio of speeds in Adelaide and Renmark regions) presumably as a consequence of increased surface friction. The effect appears to be enhanced by the mountain ranges in the coastal hinterland (cf. ratio of speeds in Melbourne region). No separation of types has been made with regard to the coastal deceleration because of insufficient sampling.

(viii) *Large-scale M.S.L. Pressure Patterns.*—Accurate tracing of air-mass history and of movement and development of the associated pressure systems is

TABLE 2

MEAN VALUES AND VARIATION WITH TIME OF DAY OF QUANTITIES RELATED TO ANALYSED COOL CHANGES

(Values in bold type indicate maxima; values in brackets are unreliable owing to small sampling)

Quantity	Station or Region	"Change"	Number of Cases	Mean	Time of Day (hr, E.S.T.)							
					00–03	03–06	06–09	09–12	12–15	15–18	18–21	21–24
Temperature fall (°F) (Questionnaire reports)	Mt. Gambier	Not specified	98	3·7	2·0	1·3	1·5	3·0	5·4	**6·0**	2·0	3·0
	Essendon	Not specified	73	5·4	2·4	2·6	1·0	5·6	**8·0**	7·0	6·5	5·1
	East Sale	Not specified	50	6·4	5	6	6	4	7·5	**11**	5	4·5
	Wodonga group	Not specified	51	7·6	5·9		(6·0)	3·3	4·7	**8·0**	7·6	5·9
Temperature fall (°F) (Synoptic reports)	Amsterdam I.	Not specified	73		2·1	1·2	2·7	**4·0**	3·8	3·2	2·0	3·4
Orientation	South Central Victoria	Not specified	50	35	34	—	30	34	35	**50**	36	34
		Single	17	43	32	—	—	41	44	**55**	39	—
		Complex { Leading	19	26	33	(—8)	45	28	26	**37**	26	34
		Complex { Trailing	14	35	34	—	(26)	34	28	**50**	48	35
Speed (m.p.h.)	Mt. Gambier to Essendon	Not specified*	49†	23·9†	16·8	(21·4)	19·7	20·9	**31·8**	31·1	21·5	18·2
	Essendon to Gabo I.	Not specified*	44‡	24·0‡	16·9	18·8	(30·3)	**28·5**	25·4	26·7	25·8	25·1
	South Coast (Mt. Gambier to Gabo I.)	Not specified	93	23·9	16·8	19·3	22·4	25·4	**29·9**	29·4	23·7	21·7
	Adelaide region	Not specified*	40	22·5	23·5	25·0	14·0	17·4	20·5	**29·3**	20·8	27·0
	Melbourne region	Not specified*	40	22·9	17·7	15·0	13·0	20·3	16·6	**22·0**	20·2	33·8
	Means of regions	Not specified	312	22·1	18·0	18·5	19·5	22·8	24·8	**26·0**	21·3	21·8
		Single	111	23·5	15·5	18·6	19·9	21·8	**29·7**	26·9	24·1	24·3
		Complex { Leading	106	22·9	20·6	22·4	22·6	22·4	23·6	**28·8**	18·6	20·6
		Complex { Trailing	95	19·6	18·9	14·4	16·4	**24·9**	20·2	20·9	20·7	19·8

Ratio of speeds (Acceleration)	(Essendon–Gabo I.)/(Mt. Gambier–Essendon)	Not specified	44	1·16	1·04	1·59	1·84	**2·58**	1·42	0·92	0·7	0·74
		Single	15	1·28	(1·67)	—	—	3·12	1·87	(1·05)	0·67	1·18
		Complex Leading	17	1·16	0·75	(0·59)	—	**2·31**	1·34	0·80	0·68	0·80
		Complex Trailing	12	1·02	1·01	—	1·84	—	1·09	0·61	0·86	0·49
	Adelaide region§	Not specified*	34	0·95	(0·88)	1·37	(1·02)	(1·43)	1·06	0·74	0·70	0·77
	Renmark region§	Not specified*	31	0·89	0·81	0·79	0·96	(0·35)	1·52	0·95	0·75	0·78
	Melbourne region§	Not specified*	32	0·78	1·30	(0·64)	0·94	1·53	0·61	0·58	0·58	0·35
	Mean of regions	Not specified*	141	0·96	1·06	1·08	1·17	**1·71**	1·12	0·83	0·68	0·72

* Distribution for classes not reproduced, but used in various ways elsewhere in the present paper (see in particular Tables 3 and 4, Figs. 3 and 5).

† Single: 17 cases, mean 25·6; leading: 18 cases, mean 24·5; trailing: 14 cases, mean 20·9.

‡ Single: 14 cases, mean 26·3; leading: 18 cases, mean 24·0; trailing: 12 cases, mean 21·3.

§ Here ratio of speeds refers to sections 100 miles downstream and 100 miles upstream from station indicated.

rendered impossible owing to great uncertainty of analysis over the ocean. However, a brief examination was made of the relationships between changes and the pressure systems with a view to detecting outstanding differences, if such occurred, between single and complex changes. There appears a somewhat greater tendency for complex changes to be preceded by strong meridional (geostrophic) flow—10 out of 21 cases as against 4 out of 19 with single changes; and to be followed by a broad west to south-west stream often with further minor front-like changes in it, 17 out of 21 as against 7 out of 19.

TABLE 3

OCCURRENCE (FREQUENCY) OF SPEED RATIOS

(Sample of data as in Table 2, last row)

"Change"	Ratio of Speeds							
	$\leqslant 0{\cdot}49$	0·50–0·74	0·75–0·99	1·00–1·49	1·50–1·99	2·00–2·49	2·50–2·99	$\geqslant 3{\cdot}00$
Not specified	24	34	33	28	12	6	2	1
Single	13	13	10	8	4	1	1	1
Complex—								
Leading	7	14	16	7	3	5	1	0
Trailing	4	7	7	13	5	0	0	0

Another difference was found in the frequency of low centres moving south-eastwards from the northern or central parts of the Bight, or eastward from its southern parts, passing over or just to the south of Tasmania. The relative frequencies were 18 out of 21 for complex changes and 11 out of 19 for single changes. Usually these depressions intensified as they approached Tasmania.

Very few distinguishing features were noted in the positions of the large-scale systems, as, for example, in the average latitude of the low centre and of the associated anticyclones; nor was there, somewhat surprisingly, any significant difference of pressure at the centres of these migrating systems.

IV. DIURNAL VARIATIONS

(*a*) *The Data*

Reference to earlier studies has been made in the introduction (Section I), especially to Loewe's investigations. He considered three sets of statistics for Melbourne: one derived from a consideration of cool changes with a following appreciable and sustained rise of pressure; another by selecting only changes with a temperature fall in excess of 10°F; and a third comprising changes designated as cold fronts on the weather maps analysed in the Commonwealth Bureau of

Meteorology. Each set exhibited the maximum frequency of incidence in the afternoon, and the third set revealed also an early morning secondary maximum.

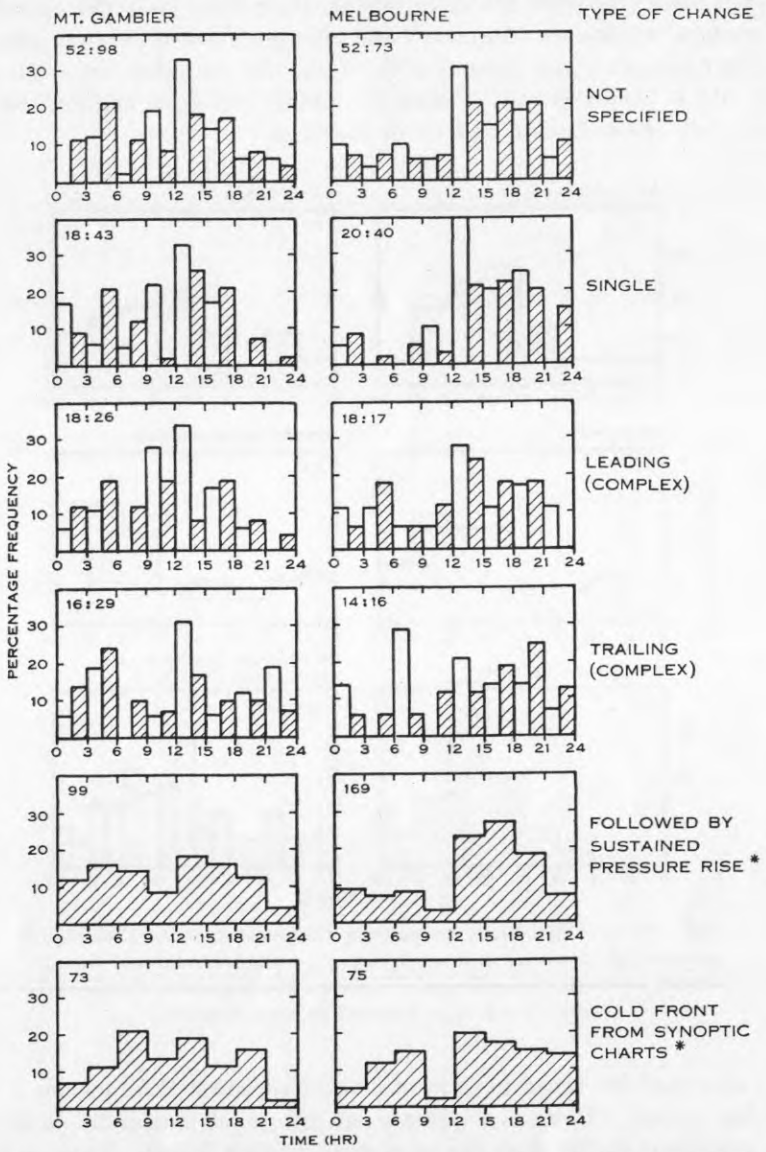

Fig. 2(*a*).—Three-hourly percentage frequencies of cool change passages at Mt. Gambier and Melbourne. Open rectangles, analysed cases; shaded rectangles, questionnaire reports. The respective number of cases of each type is stated on each diagram. * After the study by Dr. F. Loewe (1945) who kindly supplied the 2-hourly frequencies.

In Figure 2 are set in histogram form averages obtained separately from the questionnaire key stations and from a number of analysed cases, both sets from the

1953–54 and 1954–55 summer seasons. For comparison, some of the statistics given by Loewe and also data for Amsterdam Island are shown. The values obtained from the analysed cases (1953–55) are more reliable than those from the questionnaires, in that spurious reports are eliminated and changes masked at some places owing to overnight passage are not missing in the data. On the other hand, the sampling is smaller and is biased in that it mainly contains the more marked changes and only those that affected most regions in the area.

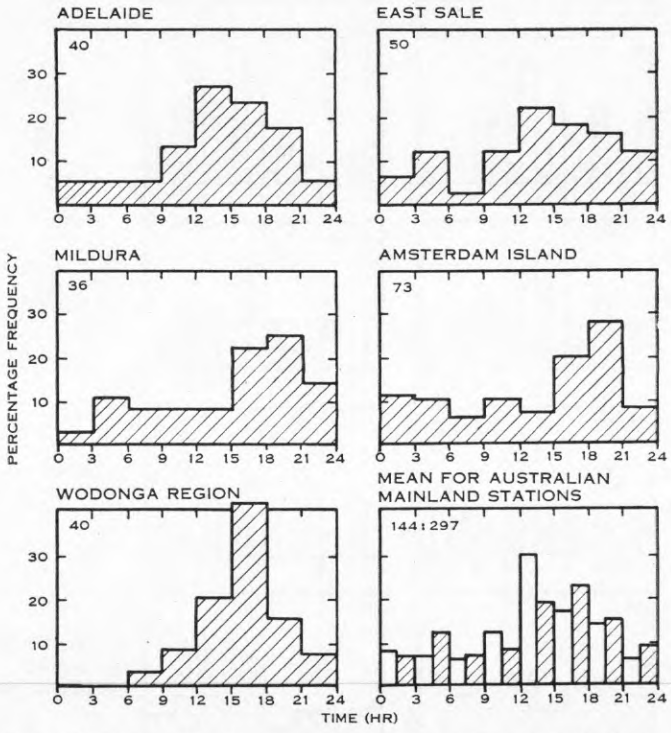

Fig. 2(*b*).—Three-hourly percentage frequencies of cool change passages at places as indicated. Open rectangles, analysed cases; shaded rectangles, questionnaire reports. The respective number of cases of each type is stated on each diagram.

It is seen that the broad pattern of diurnal variation of frequency is the same as found by Loewe. There is evidently an afternoon maximum at all stations occurring somewhat earlier near the coast than further inland. There is at several places also an early morning maximum of frequency.

Since the main maximum frequency occurs during the same *general* period of the day at all listed (Australian) stations, it cannot be simply due to a preferred time of passage of change-line well to the westward or a preferred time of frontal formation. If this were so, the resultant diurnal maximum of frequency would pass across the area under consideration in accordance with the average speed of movement. A diurnal variation of speed, however, would result in a variation of

frequency, the phase of which at each place would depend on the initial frequency distribution of change-lines upstream. Generally, the frequency is determined by the average speed (c) and the change density (ρ), since

$$\frac{N}{\delta t} = \frac{N\delta x}{\delta x\,\delta t} = \rho c, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where N is the number of occurrences in the time interval δt and δx is the average displacement in the vicinity of the considered place during this interval (3 hr in the present treatment).

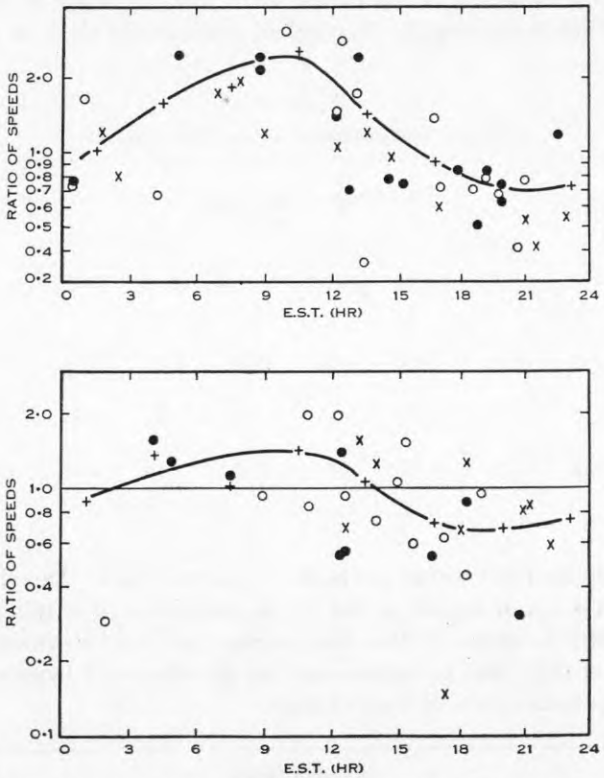

Fig. 3.—Diurnal variation of speed ratio. ●, leading change; ×, trailing change; ○, single change. Upper, ratio: Essendon–Gabo Island to Mt. Gambier–Essendon; Lower, ratio: 100 miles downstream to 100 miles upstream from Adelaide.

Whereas Loewe failed to detect a significant evidence for diurnal variation of speed, the figures in Table 2, based on considerably more detailed information—nearly all questionnaire reports have gone into the analyses—clearly indicate the diurnal variation. Changes passing Essendon between 1400 and 0100 hr E.S.T. are generally retarded as they move eastward, those passing between 0400 and 1400 hr are predominantly accelerated, most of them strongly. This result may be

of considerable practical importance for the forecasting of cool changes on the New South Wales coast as giving an indication of the time of passage at Gabo Island.

The bimodal frequency distribution relating to a leading change is well brought out in Figure 3 in the Mt. Gambier to Gabo Island set, to a lesser extent in the Adelaide set. It is seen that the modes are closely linked to the time of day when the change passes Essendon and Adelaide respectively, in such a manner as to suggest that two distinct processes influence the propagation of the changes of this type.

It appears that all types participate in a diurnal variation of speed of movement and also in a variation of orientation such that the angle of intersection with the general coastline is observed to be smallest at about the time, or somewhat later,

TABLE 4

DIURNAL DISTRIBUTION OF CHANGE DENSITY

"Change" Density	Time of Day (hr)								Variance (σ)
	00–03	03–06	06–09	09–12	12–15	15–18	18–21	21–00	
ρ'_q	0·12	0·19	0·16	0·12	0·22	0·25	0·20	0·11	$2{\cdot}36\times10^{-3}$
ρ'_a	0·21	0·15	0·13	0·17	0·17	0·22	0·21	0·17	$0{\cdot}89\times10^{-3}$
ρ'_q/ρ'_a	0·53	1·27	1·23	0·71	1·29	1·14	0·95	0·65	—

when the land-sea contrast would produce its greatest effect. This diurnal variation of orientation in a given region would be the reflection of a slight corresponding (counter-clockwise) rotation of the change-lines as they traverse the region at preferred times of day, and so emphasizes the problem of a large-scale, sea-breeze type effect on certain types of cool changes.

(*b*) *Analysis*

Variations with time of day of frequencies, average speeds, and average ratios of speed must be necessarily interrelated when the frequency of passages was determined from the set of analysed maps on which in almost all cases the lines were traced along the entire coastal belt, seemingly as continuous. (Much doubt was thrown on the continuity of change-lines on occasions in the region in western Victoria and South Australia centred on Nhill, which is known to be a favoured region for wave inception and cyclogenesis. However, rupture and distortion of change-lines in that region, although these are likely to be highly significant in other contexts, will have little affected the various sets of statistics discussed here.) The diurnal frequency distribution of changes reported in questionnaire returns, in that it differs from that of analysed cases, reflects the wider coverage of area,

spurious changes of local nature (see Section IV(a)), but probably most strongly the inclusion of changes which either formed or faded away in the area. Thus a change density evaluated from analysed cases ought to vary less with time of day, whereas a change density computed from questionnaire key stations ought to show considerably stronger variation. To test this criterion, speeds were weighted in accordance with the total number of cases in each region. Single and leading changes only were considered in the calculation of speeds. The change densities are set out in Table 4. As is seen, the variability of ρ_q (density derived from questionnaire

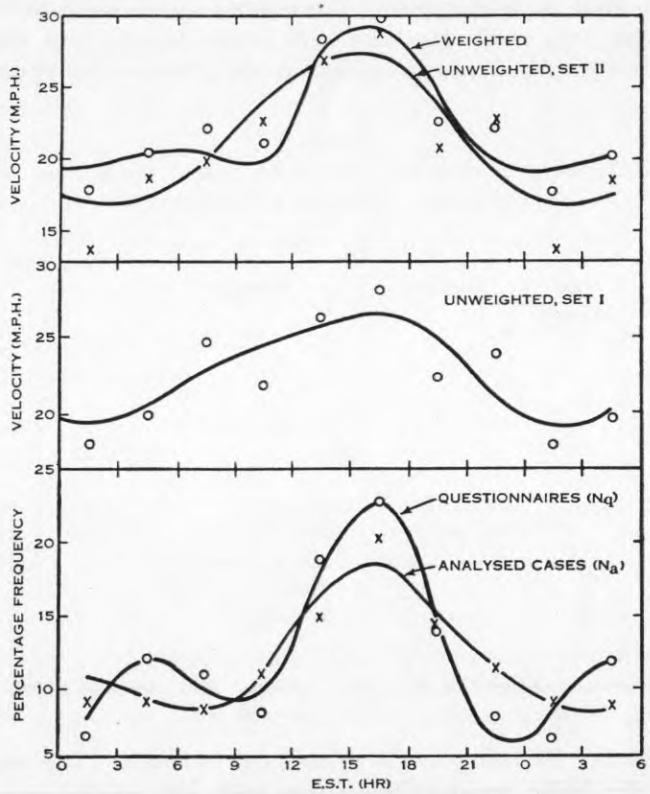

Fig. 4.—Variation with time of day of speed and of frequency of occurrence. Curves fitted using 12- and 24-hr harmonics.

reports) is rather greater than of ρ_a (density derived from analyses in the Division of Meteorological Physics), the respective variances being $2{\cdot}36\times10^{-3}$ and $0{\cdot}89\times10^{-3}$ respectively. (In the table the density $\rho'=N'/3c$, where N' is the frequency expressed as percentage of the total and c is the weighted average for the whole area.)

From the distribution of the ratio ρ'_q/ρ'_a $(=N_q/N_a)$ it is evident that afternoon events are more frequently reported in questionnaires; this might well be due to inclusion of some sea-breezes and weak coastal fronts at stations in the coastal belt. Yet, the even higher ratios in the early morning hours, stemming largely from the Mt. Gambier reports, suggest that there is a preference of arrival for weak or rapidly

weakening changes during those hours. The low ratios during the late evening and early part of the night may be attributed to masking of effects at passage, due to high vertical stability in the nocturnal inversion and, on occasions, to preceding sea-breezes.

The occurrence of two maxima in the diurnal frequency and speed distribution merits closer analysis. The first and second harmonics, i.e. oscillations of 12- and 24-hr period, were fitted to the percentage frequencies N_a and N_q and to speeds. The results are shown in Figure 4 and Table 5. As is seen from Figure 4 the fit is very good in some curves. Unweighted speeds show little of the semi-diurnal variation, but, as the goodness of fit is considerably less, this need not be significant. The data (Set I) of unweighted speeds is the same as in weighted speeds,

TABLE 5

24- AND 12-HOUR HARMONICS OF FREQUENCY AND SPEED. SINGLE AND LEADING CHANGES TREATED AS ONE CLASS. TRAILING CHANGES OMITTED

	Data Source*	Averages	Sample	Amplitude		Phase (hr)	
				24 hr	12 hr	24 hr	12 hr
Occurrence (% Frequency)	Q	—	Key stations	5·74	4·94	14·6	11·6
	A	—	Table 2	4·49	1·92	12·4	13·9
Speed	A	Weighted	Table 3	4·65	1·76	14·5	11·3
	A	Not weighted	Table 3 (Set I)	3·75	0·84	15·3	17·9
	A	Not weighted	Table 3, Essendon to Gabo I. omitted (Set II)	5·37	0·38	15·0	11·0

* Q, Questionnaire reports; A, analyses in Division of Meteorological Physics.

while in Set II the Essendon to Gabo region is excluded. The reduction of the amplitude of the 24-hr variation when this region is *included* suggests that the processes responsible for the variation are more pronounced in the western parts of the area where the orientation of the coastline differs but little from that of the change-lines, on the average.

This is amplified by noting that the amplitude for weighted speeds is larger than for unweighted speeds of Set I.

The results of this analysis lend support to the hypothesis of an influence of differential heating on the movement of change-lines, which effect was believed to be evident from the diurnal variation of line orientation in central Victoria (see Section IV(a)).

There is surprisingly close agreement in the phases of frequencies N_q and weighted speeds, with regard to both the 12- and 24-hr harmonics, whereas there is

a shift of about 2 hr in the phases of N_a and speeds. Again, Set II of unweighted speeds agrees well in phase, for both harmonics, with the frequencies N_q.

An in-phase relationship of the overall frequency of cool changes (q) with the speed from a selection of cases biased towards more marked changes must be regarded as fortuitous. The broad in-phase relationship within a homogeneous set of observations (weighted speeds and N_a) is more significant, as the ratios of the harmonics are nearly equal; 2·64 for weighted speeds, 2·36 for frequency. It is the comparatively small diurnal variation of change density which yields the aforementioned broad parallelism of frequency and speed.

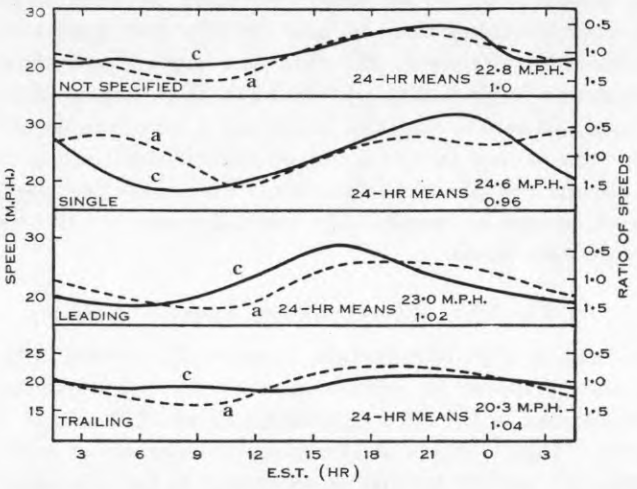

Fig. 5.—Variation with time of day of speed (c) and of ratio of speeds (a) along an average distance of 220 miles. Note that, owing to inversion of scale for a, an apparent in-phase relation represents a 12-hr out-of-phase relation.

It was not practicable to analyse the diurnal variation of acceleration separately in the different regions or as an average for the above sample of speed. However, a separate homogeneous sample has been treated, and the averages for the whole region are shown in Figure 5. Ratio of down- and upstream speeds following each individual change-line—the average translation being about 230 miles—are plotted increasing downwards so that a peak in the curve is a maximum deceleration, a trough a maximum acceleration. Unit speed ratio is made to coincide at ordinate with the mean speed for the day. The outstanding feature in the set of curves is a roughly 6-hr phase lag of speed with regard to acceleration, for single and leading change-lines. Such a phase lag is kinematically consistent with a negligible, small change of phase (in c) in the general direction of propagation. The smallness of such phase variation is evidenced by the large residual magnitude of the amplitude *after* the averaging of speeds over a wide region (compare also Table 2). For, if one takes the distribution as being represented mainly by a 24-hr simple harmonic variation with

amplitude c_0 and phase angle α, it follows from the general relation

$$\frac{\mathrm{d}c}{\mathrm{d}t} = \frac{\partial c}{\partial t} + \frac{c\partial c}{\partial x}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

with

$$\frac{\partial a}{\partial x} = 0,$$

that

$$A_0 \sin(\nu t+\beta) = \nu c_0 \cos(\nu t+\alpha), \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where A_0 is the amplitude of $\mathrm{d}c/\mathrm{d}t$ and β is its phase angle. From equation (**3**) it follows directly that $\beta=\alpha-90$, or that velocity lags behind the acceleration by 6 hr. There appears, furthermore, to be some distinction between single and leading changes, the former attaining their highest velocity and deceleration in the late evening, the latter in the afternoon. However, as a larger sample shows less evidence for this distinction (see Table 2, fifth and sixth row from bottom) it may not be real. On the other hand, all sets of statistics bring out a very considerable reduction of variations with time of day in speed and acceleration of trailing changes, and it is difficult to discern the phase relationship. The behaviour suggests, however, that this type of change is considerably less influenced by the diurnal cycle of heating and related processes.

(c) *The Effect of the Oscillating Pressure Gradient*

As mentioned in the introduction (Section I), coastal intensifications of horizontal pressure gradient in connexion with diurnal oscillations have been qualitatively established in the cited publication in which 9 a.m. to 3 p.m. pressure falls were treated. Direct effects of the diurnal variations of horizontal pressure gradients on wind are usually treated as secondary to the solenoidal circulation of the sea-breeze and are referred to as "tidal components" (Pearce 1955). Both kinds of motion are of course set up by differential heating between land and sea, and it has been found (Cassidy 1945*a*; Clarke 1956; Reid 1957) that in some way or other they affect certain regions of the Australian hinterland up to a distance of 200 miles from the coast.

A detailed study of the effects of differential heating on the behaviour of fronts and front-like disturbances such as the coastal front or the sea-breeze front approaching a heated strip of land, and of effects after the cold air has crossed the coast, would require a full theoretical treatment or at least a working model, both of which are at present not available in any form. It was thought possible to get some insight into this very complex problem by an evaluation of the geostrophic and isallobaric components of surface wind produced by the oscillation of the horizontal pressure gradient.

The departure of station level pressure (from its daily mean) at synoptic observation times (see Fig. 10) was evaluated at Adelaide, Mildura, and Mt. Gambier for the months December–February 1951–54. These departures were analysed by fitting the first two harmonics (24- and 12-hr oscillation) to each of them. Comparison of the harmonic coefficients for Adelaide with those obtained in the Commonwealth Bureau of Meteorology from hourly pressures for a period of 21 years showed that

at this station the errors due to reduction in number of observations during the day and to the shortness of the period were small, and it could therefore be assumed that they were not serious at the other two stations. Oscillations of the pressure gradient—taken as a mean over the triangle formed by the stations—were then obtained from the differences of average departures, actual ones as well as those from the fitted curves.

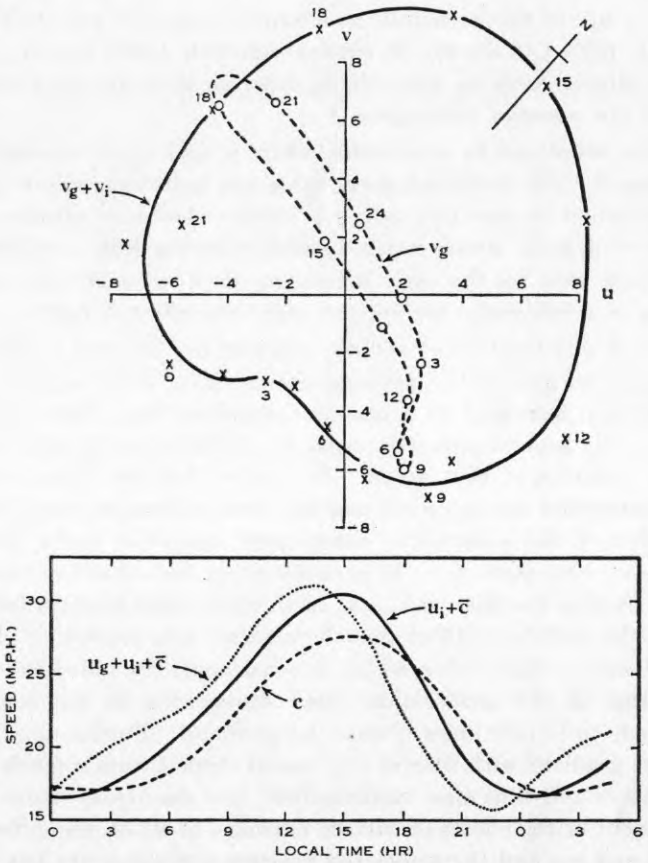

Fig. 6.—Diurnal cycle of geostrophic and geostrophic-cum-isallobaric winds computed from 12- and 24-hr harmonics of pressure at Adelaide, Mildura, and Mt. Gambier. Upper: Areas swept out by vector winds. Numbers at end-points denote hr C.S.T. Lower: Sum of average speed of cool changes ($\bar{c}$) and components of computed winds in average direction of movement of changes. For comparison curve for c is also shown.

Consider the point between Adelaide and Mt. Gambier which together with Mildura and Mt. Gambier forms a right-angled triangle, and let x denote the coordinate pointing to the former, y pointing to the latter station. The y-axis is then broadly parallel to the coastline in that region and it is almost exactly tangential to the average orientation of the change-lines in this region, as found from a check on

analysed cases (see also Tables 2 and 4). The geostrophic wind components in this system of coordinates are given by $u_g = -(1/f\rho)\,(\partial p/\partial y)$ and $v_g = (1/f\rho)\,(\partial p/\partial x)$ in the usual notation (but f being negative), and area averages were computed from the pressure differences directly as well as from the fitted curves. The isallobaric components were computed from the latter, the x-component being determined by

$$v_i = -(\nu/f)\,(u_1 \cos \nu t - u_2 \sin \nu t + 2u_3 \cos 2\nu t - 2u_4 \sin 2\nu t), \quad ..(4)$$

where $u_1, \ldots, u_4$ are the harmonic coefficients of u_g, and $\nu = 2\pi/T$, T being the length of day ($\nu/f = 1/(2 \sin \phi)$). A similar equation holds for u_i. The effects of variations of density were as usual disregarded as they are very small compared with those of the pressure differences.

The areas swept out by the vector winds v_g and $v_g + v_i$ during the 24 hr are shown in Figure 6. The combined geostrophic and isallobaric effect of the changing pressure distribution is seen to produce a counter-clockwise rotation of the wind, with an onset of a quite strong north-westerly between 0600 and 0900 hr, backing to south through west by the early afternoon, then to south-east, and decreasing while backing to north-east. During the night the effect is rather small.

The change with time of day of the component $(u_g + u_i)$ and u_i in the x-direction, i.e. the outward normal to the average change-lines, is also shown (Fig. 6), the values having been increased by a constant equalling that of the average speed of change-lines in the general region in order to facilitate comparison with the curve fitted to the variation of that speed. It is seen that the phase shift by 2–3 hr between the computed average wind and the average change speed is the effect due to the inclusion of the geostrophic component, since the curve for u_i is almost exactly in phase with that of c. It is noteworthy, too, that the amplitude in the variations of c is little less than of $u_g + u_i$ or u_i, which must be regarded as fortuitous. For, whereas the isallobaric effect may be genuine with regard to phase when the average effect over a fairly wide region is considered, the influence of friction and non-linear terms in the acceleration (both disregarded in the derivation of the isallobaric wind, as is well known) must be profound. Furthermore, the variation of the pressure gradient with time of day was evaluated from a much larger sample, including all days and thus also "undisturbed" and sea-breeze situations. A more general treatment of the effects of surface heating—of which the differential heating between land and sea and the associated pressure variations are but one aspect—is being carried out and the results will be communicated elsewhere.

V. Associated Changes in the Lower Troposphere

As mentioned in the introduction (Section I), the paucity of aerological data severely restricts a three-dimensional representation of the travelling disturbances. In particular, it was not possible, except on a few occasions, to distinguish on the upper air charts between the frontal zones (if such existed) corresponding to the steps of change complexes at the surface.

(*a*). *Relation to Large-scale Pressure Troughs*

Various statistics bearing on the relationship of surface cool changes to the large-scale tropospheric troughs have been obtained. They are not quite homo-

geneous, as individual events had to be omitted from different sets of averages, owing to missing information, but no serious misrepresentation should result from these omissions.

There seems to be no evidence of a clear-cut connexion between the 700-mb trough on the charts prepared by the Commonwealth Bureau of Meteorology and the surface change-lines analysed in the Division. When no connexion was found, the trough was either too weak to be detected in the network of upper air sounding and winds, or was very shallow and disappeared at the 700-mb level. In either case, the strong temperature contrasts associated with the surface change must be limited to the lowest 5000–8000 ft. In the remaining cases, there is a wide scatter of east-west slopes from the surface change-lines to the 700-mb trough, particularly in the northern parts of the area (30–35° S.). In part the scatter is a reflection of differences in orientation of the trough, but taking the slopes in a direction normal to the 700-mb trough gave a large scatter too.

Nevertheless, averages of various parameters of the trough configuration (set out in Table 6) bear on the distinction between the classes of changes. It follows from a consideration of slopes in the lowest 10,000 ft (surface to 700-mb level) that single change-lines tend to be skewed relative to the trough while change complexes are not; thus the latter appear to be more closely linked to the migrating troughs. Since these do not show any significant differences of orientation, as between the types, the difference in variation, with latitude, of slopes must be merely the influence of differing thermal structure in the lower troposphere.

The slopes of the upper trough (700–500 mb) are seen to be much steeper than surface –700 mb slopes. Troughs associated with single changes are less "open" (having smaller trough angle as defined in Table 3), exhibit less change of openness with height, and also slope less steeply. The smaller vertical shear (in direction of geostrophic wind) behind the trough suggests a weaker incursion of cold air with single changes, and this is confirmed by the average interdiurnal temperature change in the lowest 10,000 ft (see Fig. 7). The generally steeper slope of troughs linked with the complex changes must be a consequence of the greater horizontal shear which is apparent from the larger trough angles after account has been taken of the average surface orientation of change-lines. The shear acts in opposition to the effect of the greater temperature difference which would produce a smaller slope on applying Margules's formula for an equilibrium frontal surface to the baroclinic zone in a trough. The small values of the vertical geostrophic (direction) shear in the pre-change air, observed in both types, is noteworthy. The scatter of wind directions around the average before trough passage was found to be small for both types, in the majority of cases being well within 45°.

The data in the last three columns of Table 6 are consistent with the findings in Section III (*b*) that complex changes produce strong, and single changes weak, overall surface cooling. Changes producing largest cooling ($\leqslant$15°F) stand out in being associated with strong vertical shear in the cold air, and so indicate the occurrence of strong temperature contrasts through a deep layer of the troposphere. At 700 mb the troughs of these stronger changes assume the character of open waves in the westerlies. The more meridional direction of the warm air flow indicates

TABLE 6

AVERAGE TROUGH CONFIGURATION IN RELATION TO CLASSES OF "CHANGES" AS INDICATED

	Level	Latitude	"Change" → ↓ Single	Complex		24-hr Temperature Fall at Essendon		
						<10	10–15	<15
*Slope**:				Leading	Trailing			
Change-line to trough	Surface–700 mb	35	1/124	1/189	1/154	1/127	1/116	1/136
		40	1/213	1/182	1/173	1/204	1/217	1/182
Upper trough	700–500 mb	35	1/103	1/46		1/103	1/60	1/18
		40	1/64	1/38		1/50	1/30	1/34
Orientation of trough†	700 mb	30–35	2·2	2·0		3·3	3·0	−0·8
		35–40	1·4	1·3		2·0	2·5	−1·2
Geostrophic Wind Direction:								
Preceding trough	700 mb	35–42	301	320		300	313	322
Following trough			233	219		225	238	214
Angle of trough	700 mb	35–42	68	101		75	75	108
Preceding trough	500 mb	35–42	301	317		305	311	322
Following trough			241	235		229	240	257
Angle of trough	500 mb	35–42	60	82		76	71	65
Backing preceding trough	700–500 mb	35–42	0	3		−5	2	0
Veering following trough			8	16		4	2	43

* All averages in table were found to be positive, i.e. east to west slopes.

† Given as westward displacement of trough-line at the lower latitude from its longitude at the high latitude, in degrees longitude.

higher temperatures in the warm air, in addition to lower temperatures in the cold air, and the quasi-meridional orientation of the 700-mb troughs in these cases shows that the cold air is still vigorous in the latitudes concerned, since it is observed that surface change-lines tend to a more zonal orientation as they approach the northern limit of their penetration. The differences in the surface–700 mb slope, with the weaker changes having steeper slope, are again in accordance with earlier results. There is, however, little to distinguish the groups with moderate and weak falls of temperature. Effects such as radiation cooling and variability of cloud cover are likely to be predominant in the interdiurnal temperature falls for weaker changes, so that the criterion for grouping according to surface falls will lose its meaning.

(*b*) *Cross Sections of Temperature and Moisture Contrasts*

Average falls of temperature and changes in humidity mixing ratio in the free atmosphere, during a 24-hr interval encompassing the passage of a cool change at the surface, will result from the translation of a baroclinic zone in the first instance, but the falls will be enhanced by radiation cooling and rain cooling on occasions; and as a rule they will be reduced by the effects of convection and subsidence occurring in the pre-change or post-change air. Cross sections from Woomera through Adelaide and Laverton (Melbourne) to Cambridge (Hobart), approximately tangential to the average surface change-line, will bring out most strongly latitudinal variations of contrasts and also differences due to orography and properties of the surface. Such cross sections are shown in Figures 7 and 8. There are two outstanding features in the isopleths of cooling and decrease of total heat content (fall of equivalent potential temperature) shown in these figures.

Firstly, a rapid decrease upward of cooling through the 900–800 mb layer is evident at the two northernmost stations with both types and at Laverton with complex changes. Hobart shows a fairly uniform cooling. Secondly, average cooling throughout the lower troposphere is considerably stronger with complex changes than with single changes, especially at Adelaide and Laverton; thus are confirmed the results earlier obtained in consideration of surface variation with passage and of trough configuration (Table 6). The difference is particularly large in the lowest 5000 ft at the coastal stations. (The difference in cooling with complex changes *between* these two stations, however, may not be real since the number of cases at Adelaide, as also at Woomera, is considerably reduced owing to missing soundings.)

As is readily seen from the comparison of the isopleths in Figures 7 and 8, the pattern of decrease in total heat content (falls of equivalent potential temperature, $\Delta\theta_e$) is markedly dissimilar. With *single changes*, due to increase of specific humidity (as evidenced by the isopleths $\Delta(\theta_e-\theta)$) chiefly below and within the zone of the marked upwards decrease of $\Delta\theta$, the fall of θ_e over the continental stations diminishes upward at first and then increases again. A zone of minimum or zero change slopes steeply upward from Adelaide to Laverton. It would reflect the upper limit of the convectively mixed cool air, at which limit vertical heat and moisture transport largely compensates for advective cooling and import of air with lower moisture contents from low latitudes. At Hobart this limit would

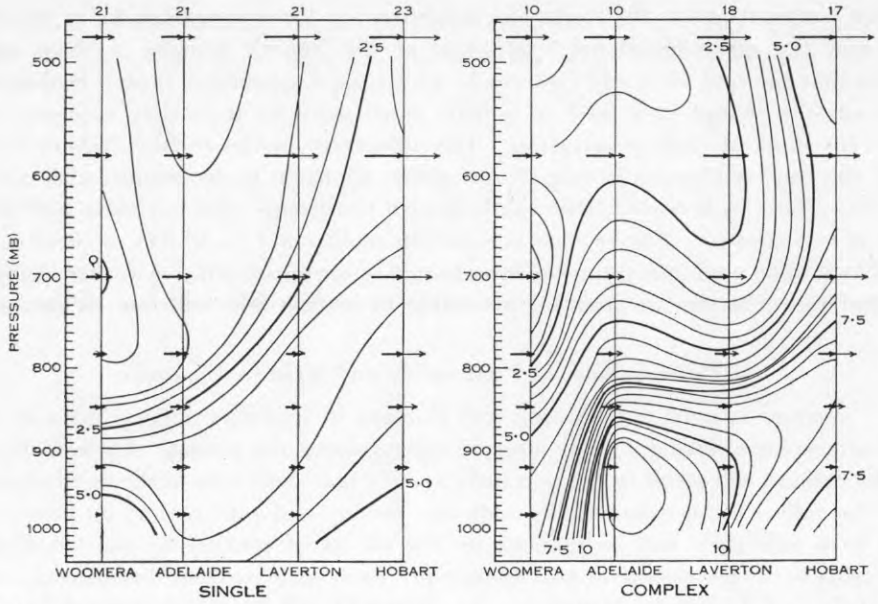

Fig. 7.—Cross sections of average 24-hr temperature fall. Number on isopleths denotes decrease in degrees C. Arrows indicate wind components normal to average orientation of change lines at surface: light arrows, before passage; heavy arrows, after passage. Number of cases for each station shown at top of vertical line corresponding to each station.

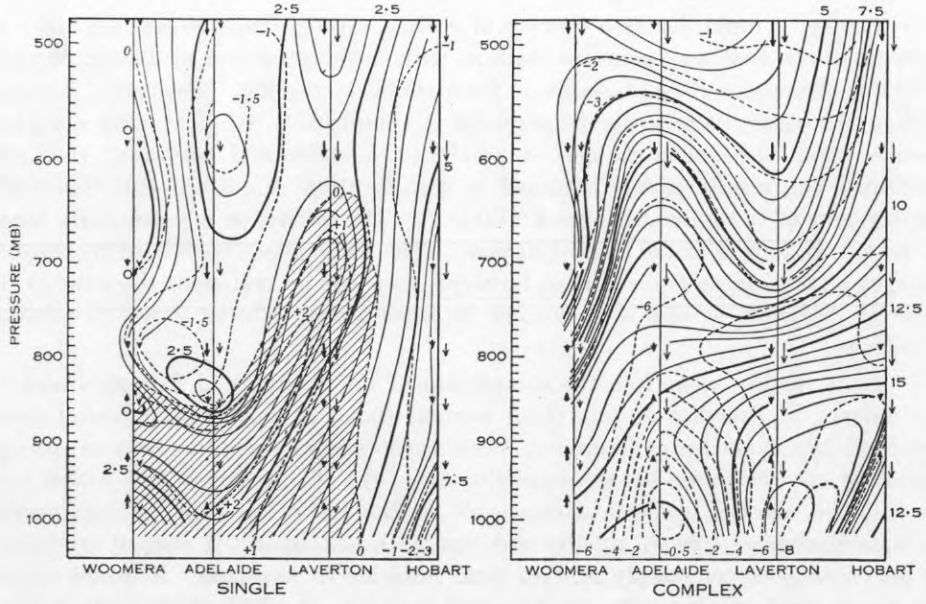

Fig. 8.—Cross sections, as in Figure 7, for equivalent potential temperature θ_e (full lines), for $\theta_e - \theta$ (dashed lines), and for wind components parallel to change lines. Number of cases the same as for Figure 7.

be above the 500-mb level. The effect of strong post-change subsidence, suggested by the small temperature falls *above* 800 or 850 mb at Woomera and Adelaide respectively and above 700 mb at Laverton, is confirmed by the secondary maxima of $\Delta\theta_e$ (associated with humidity decrease) at these levels.

With *complex changes* a different pattern of 24-hr temperature variations emerges, as already pointed out. However, the pattern of moisture changes differs radically. There is a decrease of mixing ratio throughout, except in the lowest 3000 ft at Adelaide. Whereas the strongest contrasts in $\Delta\theta$ are noted between Woomera and Adelaide in the lowest 7000 ft, the region of contrast in $\Delta\theta_e$ is there shifted to above 7000 ft. Consequently from the simultaneous distribution of moisture changes it is evident that cold air with lower moisture contents is advected into the Woomera region at least as far upward as 800 mb (7000 ft) and into the Adelaide region up to 650 or 600 mb (about 12,000–15,000 ft). The relatively small temperature falls above 850 mb in the former, and above 800 mb in the latter region, are therefore ascribed chiefly to warming by subsidence, presumably occurring mainly after the passage of the cool change at the surface. (All soundings are made at 1400 hr E.S.T., but a large proportion of changes at the surface occur in the afternoon.)

High values of $\Delta\theta_e$ at Hobart extending to the top of the considered layer and the absence of a sharp transition zone indicate the great depth of the air masses transported from higher latitudes over Tasmania. There is evident what is thought to be a significant difference between single and complex changes. Whereas with the former there is suggestion of a rapid decrease with height of $\Delta\theta_e$ up to 3000 ft, with the latter a distinct maximum of falls occurs at about 5000 ft, chiefly owing to drop in temperature. In this distribution are verified the effects of considerable over-water modification* of the warm air streaming across Bass Strait with northerly winds (discussed earlier) which are characteristic ahead of complex changes. Such modification reduces temperature and increases humidity mixing ratio, but, as the cold air too has preferred over-water trajectories, a drop in θ_e with upwards increasing rate would result from the combined effect.

The zone of maximum drop in θ_e extends northwards and downwards from Hobart to Laverton where the effect of Bass Strait is absent with complex changes. The average fall in mixing ratio at surface noted at Laverton (2·2 g/kg), at Hobart (1·8 g/kg), and Woomera (2·3 g/kg) is absent at Adelaide (rise of 0·4 g/kg) at the surface with little fall up to 900 mb. This indicates the importance of modification of the *cold* air reaching the coastal regions of South Australia on extended trajectories over the warmer waters in these latitudes. (Modification of *warm* continental air streaming from a north-westerly or westerly direction on temporary over-water trajectories will sometimes occur behind leading changes of complexes and must play an important role in the origin of certain temperature and moisture changes

* This appears to be an important process from the point of view of air mass verification on synoptic maps, although the dynamic consequences may be negligible. Some of its aspects will be treated in Part II when relevant data obtained from a series of aircraft flights over Bass Strait will be given.

observed in the Mt. Gambier region. The problem will be treated in some detail in Part II dealing with the study of selected cases.)

On a few occasions at each of the four stations a sounding happened to occur at some time between leading and trailing changes of complexes. By grouping the stations together, the separate contribution by each step to the 48-hr fall of temperature could be roughly assessed. Again, the scatter of the values around the average was very large, but the distribution of averages in the vertical may be significant. It was found that with the leading change the 24-hr cooling decreases rapidly between surface and 900 mb and vanishes at the 850- and 800-mb levels, small temperature falls occurring at higher elevations. With trailing changes the magnitude of the cooling remains the same up to 850 mb, with rapid decrease of cooling above that level, similar to the distribution in Figure 7 for the continental stations. It is true that, owing to the usual spacing of the steps in a double change, a good deal of pre-change warming (advective or by subsidence) would be included in the temperature change attributed to the leading step. Nevertheless, the small average fall at 900 mb (2°C, resulting from a number of rises and falls) is incompatible with the validity of the frontal concept in a great majority of cases, in contradiction to commonly held views (Clarke 1954). Even if it is assumed that pre-change advective warming at 900 mb were considerable on occasions with 24-hr rises, the passage of a frontal zone, other than a very weak front, would certainly nullify or overcompensate this effect. Furthermore, the increase, with time, of the depth of cold air under a frontal surface (zone) associated with an active cold front (other than a "coastal front") is all too rapid to attribute the absence of marked cooling at 900 mb to the circumstance that the soundings were made within 1 or 2 hr of the surface change on a number of occasions.

On the other hand, the slightly increased cooling associated with the leading change above 800 mb is probably a reflection of the upper cooling associated with the development of instability in the warm air (Clarke 1954).

(c) *Classification of Changes from Soundings*

The scheme of classification follows closely that given by Troup (1956) in an aerological study of the "meridional front" in Western Australia during winter. That scheme was based on the salient features in the vertical structure and humidity in the post-change sounding at Perth, the 24-hr variations at that place, and the differences in elements between Perth and Kalgoorlie at the time when the surface change lies between them. No similarly suitable pair or pairs of sounding stations exist in south-east Australia. Thus merely post-change structure and 24-hr variations will be considered, and the salient points of such a classification are set in Table 7.

Types B′ and C′ have been added to the four main types discussed by Troup.

Soundings at Woomera, Parafield, and Laverton were grouped together. Broadly, the anafront type A implies ascending motion in the warm air, the katafront types B imply descending motion, although initial extreme dryness of the warm air might be sometimes compatible with ascending motion to be associated with types B and B′. It was observed that when type B occurred a considerable time

had usually elapsed between the change passage and the radiosonde ascent, and when type B′ occurred a short time had elapsed. It may be inferred from this that type B′ represents the cooling produced by the relevant change itself, while type B includes the effect of post-change subsidence.

The nature of the types C and type D is less clear. Troup has pointed out that the distinction between C and (C′ and D) lies mainly in the behaviour of the subsidence inversion which either persists after passage (with little change of height and of potential temperature aloft) or appears at a significantly different height, presumably owing to convective rupture or the formation of a new inversion. He

TABLE 7

CLASSIFICATION OF CHANGES FROM SOUNDINGS

Type		24-hr Cooling	24-hr Moisture Changes
Frontal—	A (anafront)	Lower layers	High relative humidity on second ascent
	B (katafront) 1	Shallow layer	Marked drying above subsidence inversion
	2	Shallow layer and aloft	
Transitional—B′		Shallow layer	No drying aloft
Non-frontal—C		Below pre-existing subsidence inversion at little-changed height	Low relative humidity above inversion
	C′	Above subsidence inversion at considerably changed height	
	D	None or in lower layers.* No evidence of a subsidence inversion	No change or increasing relative humidity in lower layers*

* The equivalent potential temperature tends to remain unchanged.

alluded to the broad similarity of types C to the pressure-jump model evolved by Tepper (1950) and drew attention to the fact that a number of non-frontal changes moved at a speed considerably in excess of the normal wind component under the inversion behind them which, incidentally, is a requirement of the underlying theory. A limited survey of upper winds in the region here considered gave an indication that the ratio of the *speed* of the surface change to the mean *normal wind component* in the lowest 5000 ft at the first available post-change pilot balloon or radar wind sounding did not on the average equal unity but was somewhere larger (refer also to Section VI(*b*)).

It is of interest to relate the classification according to sequence, i.e. single, leading, and trailing changes, to the classification according to soundings (simplified to frontal and non-frontal types according to the above scheme). The proportion of non-frontal to frontal types was 12 out of 33 for single, 7 out of 9 for leading, and 2 out of 14 for trailing changes.

The occurrence of pressure jumps closely associated with changes has been noted at Laverton and the relative proportions are:

Single	Frontal	4/7	Leading	Frontal	0/0
	Non-frontal	8/8		Non-frontal	2/4
	Transitional	4/5			
Complex	Frontal	5/9	Trailing	Frontal	0/4
	Transitional	1/1		Non-frontal	0/0

The figures refer to analysed cases only, and the classification into frontal and non-frontal types of soundings was done for complex changes (both steps occurring between two soundings) from data other than those used for leading and trailing changes (a sounding between the steps). On separating merely into definite frontal and non-frontal classes,* a somewhat larger sample is available for each and the figures are: proportion of pressure jumps with frontal soundings 9 out of 20, with non-frontal soundings 15 out of 18.

The above figures suggest that, of cool changes occurring with passage of a single line of surface discontinuity and as the leading line of a double change, those not fundamentally cold fronts are a large proportion of the whole, even if allowance were made for rain cooling causing pressure jumps in a number of these. The classification according to soundings showed than in about 95 per cent. of station cases a trailing change was determined as frontal and that at Laverton no pressure jumps were noted with these.

VI. Features of the Horizontal Flow

(*a*) *Shear and Convergence near the Ground*

A glance at Figure 10 shows that the backing of wind with the passage of change-lines, observed at all places with any type (except with trailing changes at Port Augusta at the northern end of Spencer Gulf), and the associated 3-hourly change in velocity, are consistent with cyclonic horizontal shear. For it may be assumed that during 3 hours, which is equivalent to about 60 miles on the average, the wind field in a 30-mile wide strip on either side of the change does not alter appreciably. With this assumption

$$\text{zonal}\dagger \text{ shear} = \Delta v/\Delta x = \Delta v/c\Delta t,$$

and similarly

$$\text{zonal convergence} = -\Delta u/\Delta x = -\Delta u/c\Delta t,$$

where $\Delta x = 3$ hr and Δu, Δv are the 3-hourly changes of the normal and parallel components of surface wind (for definition see Section IV(*c*)).

The values of shear and convergence, computed from the average pre- and post-change winds and the average speed of changes, with due consideration to the orientation of the change-lines at the various places, are shown in Figure 9.

* The transitional class is for this purpose regarded as non-frontal.

† The zone is centred on the change-line and has a width Δx. The more familiar terms are frontal shear and frontal convergence, but these are avoided in this context.

The magnitude of the zonal shear and convergence, as defined here, is 10^{-4}—10^{-5} sec^{-1}. Owing to the assumptions made, it is not possible to compare

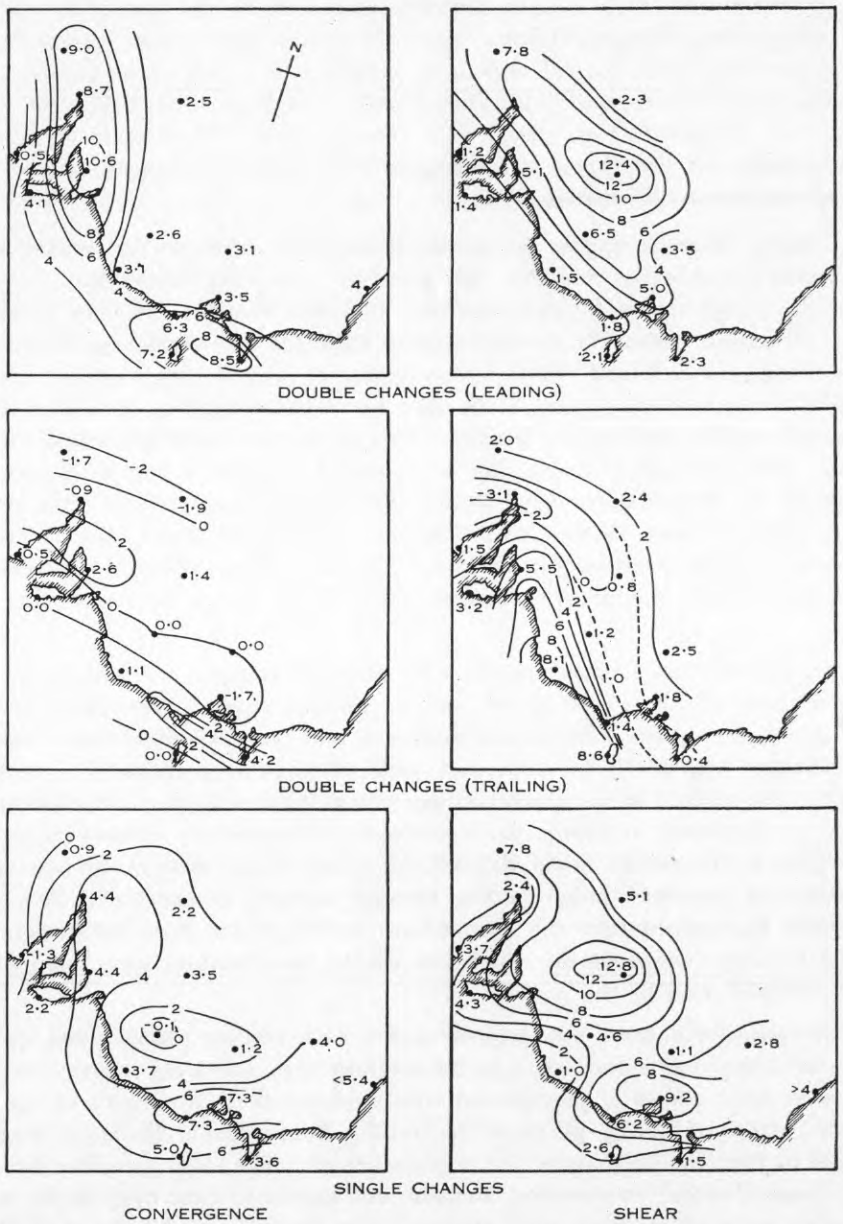

Fig. 9.—Distribution of convergence (positive values) and cyclonic shear on change-lines. Unit is 10^{-5} sec^{-1}.

the values obtained with those measured or deduced from theoretical considerations for cold frontal zones in other parts of the world. Attention is here restricted to

distribution in the regions considered and to differences that may occur between the classes of cool changes.

(i) *Shear.*—As with various features discussed in the preceding sections, single and leading changes exhibit a markedly similar distribution; strong increase of cyclonic shear from coastal regions to inland, and a belt of maximum values extending from Woomera through Port Augusta and Mildura to Melbourne, which region may be classified as inland in a consideration of large-scale topography. The comparatively low values at Deniliquin and Broken Hill indicate the northern limit of the region of marked shear.

Trailing changes appear to be associated with considerably weaker shear, high values occurring at Adelaide, Mt. Gambier, and King Island only, at which places the simultaneous temperature and humidity changes are very much the same. The main feature in the distribution indicates the weakening of the shear as the change moves inland. The average veering of wind at Port Augusta, resulting in negative (anticyclonic) shear, is thought be to characteristic, since that station is situated close to and on the windward side of the north-south oriented Flinders Range. The anomaly is caused by a prolonged backing of the wind after the passage of the first discontinuity; it suggests strongly that, at least on a number of occasions, the cool air was very shallow, and confirms the earlier indications from soundings (see Sections V(*b*) and (*c*)). The anomaly mentioned is not observed at Adelaide, which is similarly situated, although at the southern extremity of a range.

(ii) *Convergence.*—Again, single and leading changes are associated with positive values at almost all places, and, in general, coastal places show stronger convergence. In western Victoria and south-east and parts of central South Australia these changes appear to be associated with weak convergence and a minimum appears to be centred in the general region around Nhill, well over 100 miles inland. It may be of interest to note in this connexion that consistent synoptic analysis in this region is frequently made difficult by either weak changes or late arrival producing an apparent bulge in the broadly straight discontinuity line. The impression was gained that the change-lines in this region were not always continuous although occasions on which the effects were marked were not included in the samples used in this paper.

Comparatively weak convergence occurs with trailing changes and at some places the computed values of $-\Delta u/\Delta x$ are negative, indicating divergence. The absence at most places of pronounced convergence reflects proximity of the anticyclonic pattern of M.S.L. isobars to the trailing change-line, as the latter is usually detected in the rear portions of the surface trough. The effect (see Boyden 1938) of the "coastal ridge" over central Victoria, well known to forecasters in the region, is clearly shown by average zonal divergence at Melbourne, while at Cape Otway and Wilson's Promontory convergence is dominant.

No attempt was made to resolve the average wind vector into normal and parallel components at East Sale, Gabo Island, and Tasmanian stations because of the uncertainty of orientation. The varying effects of the all-important orography

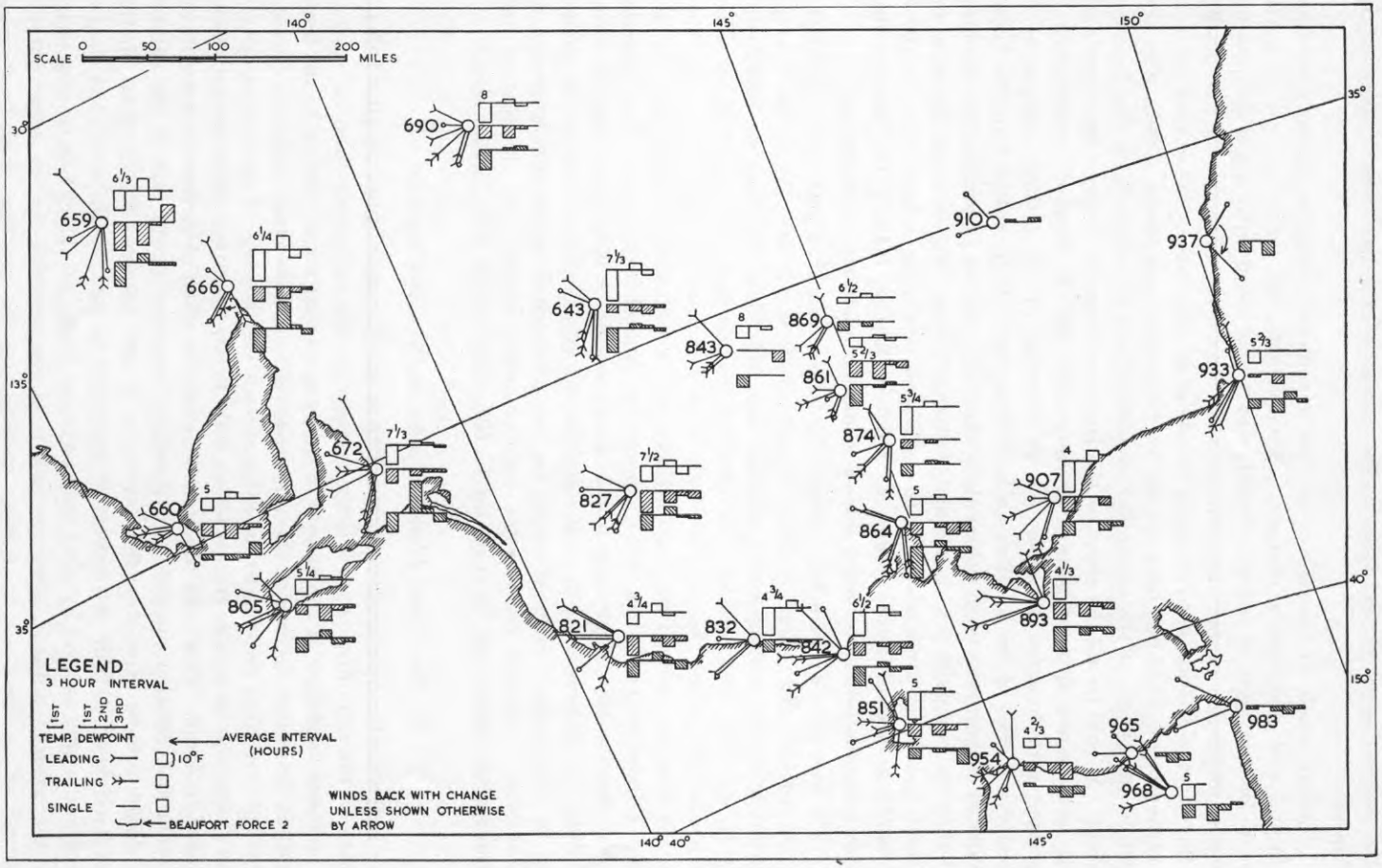

Fig. 10.—Wind, temperature, and dew-point changes from 3-hourly synoptic reports.

in the eastern parts of the area on the classes of changes cannot therefore be estimated.

Surface winds in themselves are not a sufficient criterion in the separation of frontal and non-frontal changes. Nevertheless, the prevalence of an initial increase of shear inland and northward, which was found with single and leading changes, would not support the concept that they are predominantly cold fronts; for the effect of friction is to decrease the shear at all fronts, whether they are cold or warm fronts. This has been shown by Petterssen and Austin (1942), who also discussed the effects of the solenoidal circulation and convergence on the variation of shear. At cold fronts the effect of the latter is always to increase the shear and, as is well known from dynamics of horizontal flow in general, convergence is associated with increase, divergence with decrease, in the vertical component of vorticity and thus of the zonal shear, as defined here. It is evident from the broad features of convergence (high values along the coast, with single and leading changes) that they are compatible with the distribution of shear, but, since the temperature contrast generally diminishes as the changes penetrate inland (see, however, comments on non-advective cooling at Mildura, Section III(a)), the increase due to the solenoidal effect of shear inland would be relatively unimportant.

The fact that with *trailing changes* the largest values of shear are found along the line Adelaide–Mt. Gambier–King Island, which is not very far off the average orientation of the corresponding change-lines (see Table 2), may be significant; prior to reaching that position, the effect of friction in reducing horizontal shear in a *frontal* zone would be comparatively small but would rapidly reduce the shear once the zone has crossed the coast. However, the low values at Port Lincoln and Wilson's Promontory do not fully support the frontal hypothesis. With changes *not* associated with a large-scale frontal zone, namely, a fairly large proportion of the other two classes in the present classification, effects of friction near the ground must be considerably reduced owing to less constrained momentum exchange in the vertical. Coastal convergence may therefore become the dominating and discriminating effect and be regarded as the cause of the large inland shear.

(b) *The Upper Flow* (*Subpolar and Tropical Regimes*)

Reference has been made in Section V(c) to check computation from pilot-balloon ascents on the ratio $\bar{u}/c$, where $\bar{u}$ is the average normal component from the surface to the lower boundary of the zone of maximum vertical shear. Owing to the large variations from case to case in the time interval from pre-change ascent to passage at surface and from passage to following ascent, and because of the comparatively great proportion of missing winds above 5000 ft, the results of these computations are open to doubt. This is all the more so, since the effect of convection currents on direction and velocity computed by assuming constant ascent rate of the balloon is a double source of non-random errors, as is well known. Rawin data, on the other hand, are free from the defects of one of the sources (height error) and station by station as well as level by level they are more complete. The 24-hr spacing apart and the greatly reduced coverage are thus compensated for to some extent. Although of no direct use for further investigating the problem of air-flow versus

speed of movement of change-lines, Rawin data in conjunction with pilot-balloon data give useful indications about large-scale features of the flow and complement the results in Table 6.

Average resultant directions and velocities, compiled from Rawin data at Laverton and Hobart for two seasons and from Parafield for the 1954–55 season, and supplemented by pilot-balloon observations for the earlier season there and at Woomera, are set out in Table 8.

The salient features regarding backing of wind with time and post-change veering with height in the lowest 7000 ft or so confirm the findings of Table 6. The wind directions in the 10,000–20,000-ft layer at the post-change ascent differ very considerably from the contour-line directions at the 700- and 500-mb level, being veered by 30–40°. The discrepancy is readily accounted for by the westward tilt of the trough, the almost due west direction indicating that the trough at the 15,000-ft level is on the average overhead at the time of the ascent after passage of the change.

Comparison between wind and contour direction *before* passage shows a residual veering of wind in the layer between 10,000 and 20,000 ft amounting to 16° with single and to 26° with complex changes. These values in themselves can give only a mere indication of a tendency for cross-isobaric flow towards higher pressure, but seem significant in view of the higher average velocity occurring with complex changes, namely, 28 kt as against 24 kt with single changes. The corresponding *ageostrophic* velocities are 12·3 and 6·6 kt respectively. It is also seen from Table 8 that at Laverton with complex changes the high tropospheric westerlies before are stronger by 5 kt, the stratospheric westerlies by 10 kt. Unfortunately estimates of the non-geostrophic components in the upper levels and at any level in the rear and central parts of the troughs are not possible by using this method. If similar departures in direction between contours and wind were to take place in the centre of the trough, the considerably higher wind velocities above 15,000 ft (see ascents *after* passage in Table 8) would imply even larger non-geostrophic winds and the contrast between single and complex changes would be accentuated. A generally stronger outflow towards higher pressure aloft in the regions of cyclonically curved flow and ensuing stronger divergence is at any rate consistent with the higher values of surface "zonal" convergence occurring with complex changes (see Section IV(a) and Figure 10). It has been stated in Section V(a) that the cool changes of this type, i.e. double change-line and stronger overall temperature contrast, are more frequently associated with intensifying depressions moving from the Great Australian Bight to Tasmania than with single changes. From general experience it is known that the deepening frequently continues to the time when the centre of the low is situated well over or to the south of Tasmania. The deepening process would be seated in the upper troposphere, judging from the deduced non-geostrophic winds. From the velocities at the four stations it is evident that the jet-stream on the average is located south of the continent, since at 20,000 ft the average at Hobart is 50 kt (before passage ascents) as against 31 kt at Laverton, and since in the average seasonal cross section of zonal component at 150° longitude (Loewe and Radok 1950) the line of maximum winds slopes from 42° S. at 20,000 ft to 40° at the jet-maximum

TABLE 8

AVERAGE WIND DIRECTION AND VELOCITY (KNOTS)

(Third and fourth columns, means of stations as in cross sections, Figures 5 and 6)

Change	Ascent	Average of Four Stations		Laverton					
		Level (1000 ft)		Level (1000 ft)					
		3, 5, 7	10, 15, 20	25	30	35	40	45	50
Single	Before	316 13	285 24	293 37	290 43	289 45	282 49	297 40	281 36
	After	257 14	273 29	281 45	280 59	286 52	287 54	289 53	281 45
Complex	Before	319 17	285 28	300 39	295 42	291 50	286 54	285 50	297 46
	After	243 13	265 31	291 52	292 58	293 69	290 72	280 72	281 65

height, at about 30,000 ft. The disturbances concurring with complex changes appear thus to be linked with unbalance of horizontal flow on the equatorward side of an intensified jet stream, which suggests that they are of fundamentally different nature from the disturbances concurring with single change. Intensities of the upper flow occurring with the latter are considerably lower as the Laverton velocities in Table 8 show. They are, incidentally, little different from the seasonal averages derived by Loewe and Radok (1950). To judge from the height changes of velocities, the tropopause is double, the lower (subpolar) and upper (tropical) tropopause occurring at about their average seasonal height. (Compare Radok 1952.)

The figures indicate that with complex changes the occurrence of a single tropopause at greater height is dominant and that this is the tropical tropopause. These differences lend further weight to the distinction between the disturbances in the pressure field associated with single and complex surface cool changes (Section V(*a*)), the former resembling more closely the winter type, the latter being characteristic of subtropical summer regimes.

(*c*) *Normal and Parallel Components*

A study of the average normal and parallel wind components at the four cross-section stations (see Figs. 7 and 8) is useful in connexion with large-scale vertical motion and horizontal shear. Marked 24-hr increase of normal flow is observed throughout the layer of cooling at all stations except Hobart where it prevails merely in the lowest 3000 ft. This anomaly could be explained by an orographic distortion of the flow, although such effect ought to be visible at the lower levels rather than at greater height. However, the distortion would affect the orientation of the change-lines which were traced with some confidence in the northern parts of the island only.

Increase of the *normal* component with time as well as in the vertical is predominant at the continental stations above the layer of cooling. This feature clearly proves the predominance of active subsidence ("overrunning") in the upper regions of the advected cool air where it is particularly pronounced at Woomera and Adelaide. To the extent that sloping frontal zones are existing, the prevalence of katafronts is thereby verified. Furthermore, overrunning at those stations and also at Laverton is more marked with complex changes than with single ones. From this it follows that, since in the region of overrunning $\partial w/\partial z<0$ and consequently $\mathrm{div}_2 \boldsymbol{V}>0$, horizontal divergence is stronger with complex changes, in agreement with the earlier deductions from the cross-isobaric flow.

Reversal of the *parallel* component from approximately NNW. to SSE. within 24 hr extends through the whole layer of cold air import only at Woomera; at the other stations the lower portion of that layer only is characterized by such reversal, but at all places in that layer the transport from north-north-west is smaller after than before passage. *Above* the layer, there is at Woomera and Adelaide either no change or an increase of the component under consideration which may be due to inaccurate resolution of the vector wind into the relevant components or else reflects the displacement of the baroclinic zone at these heights and latitudes relative to its position further south.

VII. Survey

Apart from the inherent value of the statistics, the foregoing discussion is thought to be of value in bringing out the distinction between single and complex changes. This has raised numerous points which bear on the varying nature of the mechanisms associated with the surface discontinuities. There appears little doubt that the process is a many-sided one since, while some of the hypotheses mentioned in the introduction are clearly untenable, no one of the others is uniquely favoured by, or wholly consistent with, the evidence. To show this most clearly the salient features of the data are now reviewed.

Much evidence suggests that a large proportion of the changes, especially of leading steps and single changes, originate as coastal fronts;* this includes the following features:

(*a*) The marked afternoon maximum frequency of incidence coupled with high speed of movement and tendency for coast-parallel orientation.

(*b*) The close or in-phase relationship between speed of movement and the diurnal cycle of differential heating. This is indicated by the inflow, across the coast, into the heat low-pressure area in the afternoon and, in a general way, the effects of the diurnally oscillating pressure gradient in the coastal belt.

(*c*) The rapid decrease of cooling with height in the lowest 3000 ft observed with leading changes; and the large number of post-change soundings with leading steps and single changes which showed non-frontal characteristics.

On the other hand, the process of coastal front activation leaves no room for the multiple changes observed on occasions; nor does it account for the semi-diurnal cycle of frequency of incidence, especially the observation of leading steps in the early morning at Mt. Gambier. Moreover, it is most unlikely that a coastal front could give rise to a sufficiently sudden and deep incursion of cold air to cause the pressure jumps frequently observed with the leading changes.

The suggestion that a lagging trough gives rise to two, or a succession of, fronts agrees with the observation that the leading change is frequently sharp and the second diffuse at the ground, at least in coastal regions. It would accord with the finding that at times the leading change moves ahead of the main trough and is retarded and weakened. However, frequently there are two well-defined change-lines separated by only about 100 miles. This seems at variance with the lagging trough model, as 100 miles' displacement would not appear to allow for appreciable frontogenesis in the lagging trough.

There is much to commend the explanation in terms of a double change of the Riehl type—a pre-frontal convergence zone produced by an upper trough, with

* The region of formation is supposed to be around the col lying off south-east South Australia and south-west Victoria ahead of an approaching front as suggested by Langford. The activation of the coastal front would produce the leading change over land.

the wind-shift lines on the ground resulting from interaction with higher layers. This or a similar mechanism is consistent with the propagation over long distances of marked narrow shear zones with little temperature contrast. It was shown that persistence inland could be accounted for by the high coastal convergence provided that ground friction were counterbalanced by continued momentum exchange with higher layers. This is precisely the mechanism envisaged by Riehl. But, judging by the frequency of pressure jumps with non-frontal change lines, it is probable that the pressure-jump line process described by Tepper will be more adequate than the vaguer concept of trough-induced convergence.

The foregoing analyses throw light on the inner mechanism of the disturbance, mainly by ruling out the cooling from evaporating rain as the primary cause of the surface pressure jump. A large proportion of the changes was dry. The mechanism of cooling in such cases follows from a consideration of air mass modification. This and other more mechanistic aspects of the problem will be more suitably treated in Part II, where a more detailed study of individual case histories will be made to supplement the mainly statistical information of the present Part I. Part II will also include a more intensive study of the wind-shear zone and its variation with height, based on data from serial ascents made in close networks in the regions around Melbourne and Mt. Gambier.

Finally, there is evidence that changes with the stronger falls in surface temperature extend their contrasts to greater heights, and have stronger winds with larger meridional components throughout and more pronounced ageostrophic components aloft. These stronger changes—which are very frequently characterized by two change-lines at the ground—appear to be associated with an intensification of a typical circulation pattern of the warm season, namely, more meridionally oriented troughs extending from the Southern Ocean and linking with the heat low over the continent. This means that the structure of the transition zone between warm and cold air masses is largely determined by oceanic-continental differences in pressure and temperature distribution, and the importance of coastal contrasts in this respect is brought out in quite another way.

VIII. Acknowledgments

The authors are indebted to the Director of Meteorology, Commonwealth Bureau of Meteorology, for the loan of instruments, for cooperation in organizing special reports from aerodrome meteorological stations, and for making available the synoptic and aerological data and other material used in this study; to Dr. C. H. B. Priestley, Chief of the Division of Meteorological Physics, for his advice and encouragement during the course of the work; and especially to their former colleague, Mr. W. W. Moriarty, who took a large part in the work, particularly in the field investigation in South Australia.

Their thanks are also due to the many volunteer observers, private citizens as well as the officers of the Commonwealth and State departments and authorities who assisted in the observations; a list of these is given in Appendix II.

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Appendix I

The observational material and its collation

The observational material may be divided into classes as follows:

(*a*) Three-hourly routine synoptic observations, made mainly in daylight, and discontinuity reports from stations operated by the Commonwealth Bureau of Meteorology.

(*b*) Autographic records maintained chiefly by the Bureau. These proved very valuable, though again the network is in general not nearly as close as might be desired.

(*c*) Routine pilot-balloon, Rawin, and radiosonde ascents made at widely scattered Bureau stations.

(*d*) "Questionnaire returns" of passage and associated weather phenomena sent in by special visual observers. Measurements of temperature fall and rainfall were also made by a number among these observers. At different times more than 100 observers cooperated and their assistance was invaluable, both in filling out the Bureau network and in providing detailed information not available from routine synoptic reports. Questionnaire returns from the meteorological offices at the aerodromes in Victoria were also obtained, and these provided the most reliable information.

(*e*) Weather observations, made at 4-hourly intervals on board some ships plying in Bass Strait, and on board naval survey vessels, giving information which bore on the behaviour of cool changes at sea.

(*f*) Thermographs and thermohygrographs provided by the Division and maintained by voluntary observers at various key points, and also on board some ships plying in Bass Strait.

During January 1956 such instruments, as well as barographs and wind direction recorders of a type developed in the Division, were maintained at a large number of places in a fairly close network in south-eastern South Australia. This network served a special extensive study of cool changes and sea-breezes. The Commonwealth Bureau of Meteorology provided a part of the instruments and one of its officers participated for some time in the field work.

(*g*) Field observations comprising closely spaced series of pilot-balloon ascents at a number of places in the South Australian region and also at Aspendale. These serial ascents were made chiefly after the passage of cool changes, or the onset of sea-breezes, or both.

(*h*) Information on the air mass properties in the lower troposphere over the sea derived from a meteorograph fitted to an aeroplane flying between King Island and Moorabbin (near Melbourne).

The locations of the permanent network stations, most of which are maintained by the Commonwealth Bureau of Meteorology, are shown in Figure 11. The locations of questionnaire stations and of the close network of stations set up by the Division during January 1956 are shown in Figure 12. The cooperating authorities are listed.

The observations were collated, broadly, in three ways. Firstly, an endeavour was made to trace the movement of the change-lines, and to infer the nature of the physical processes involved in the maintenance and movement of the changes; secondly, the data, both raw and analysed, were averaged in various ways to obtain a tentative statistical or climatological description; and thirdly, the serial upper wind observations were studied in conjunction with the dense network of autographic records in the South Australian and Greater Melbourne regions.

When using the questionnaire returns from private observers it was always necessary to bear in mind the possibility of spurious reports of changes owing to

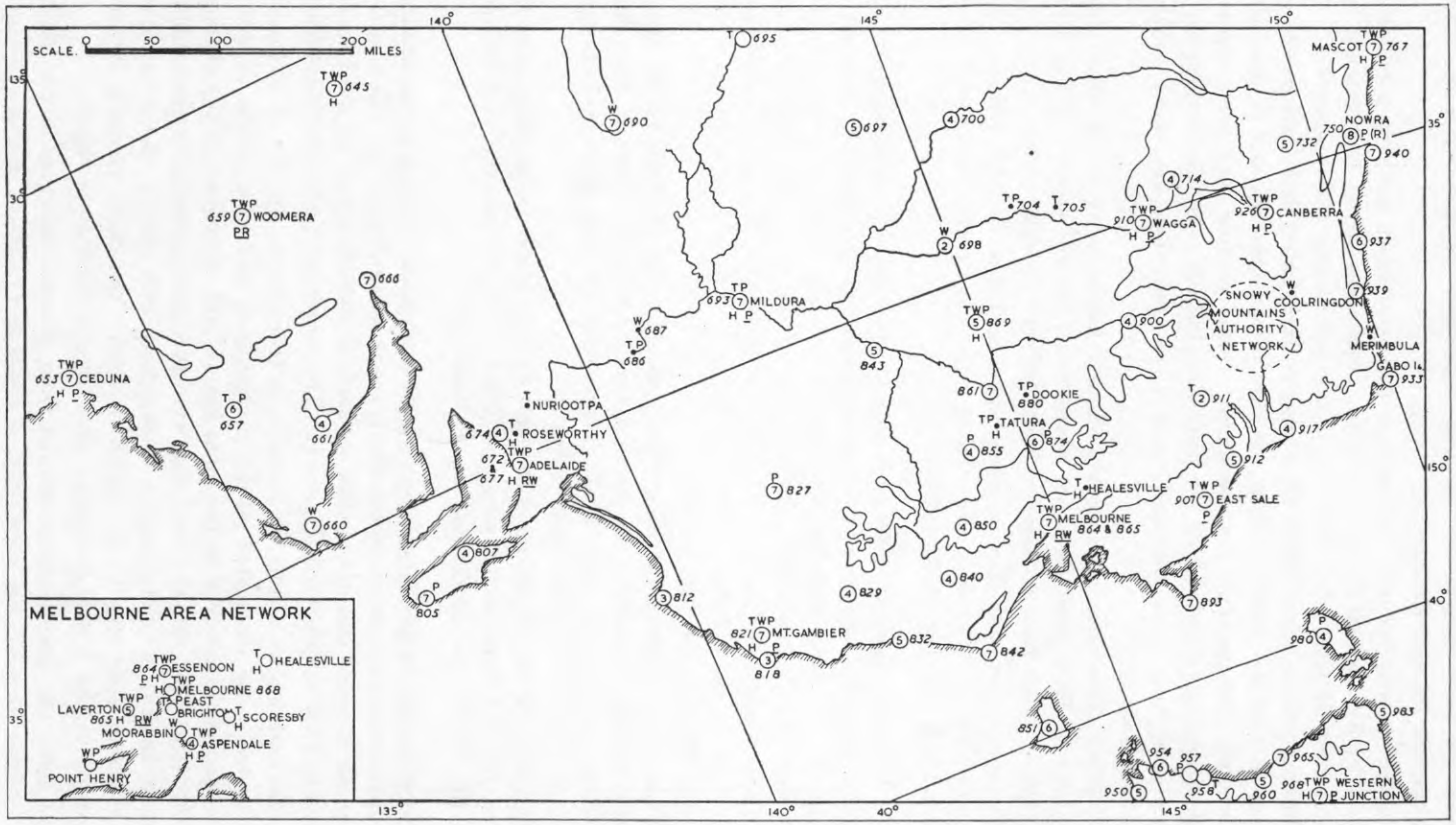

Fig. 11.—Permanent network. n (in circle), number of 3-hourly synoptic observations per day; P, station equipped with barograph; W, station equipped with anemograph; T, station equipped with thermograph; H, station equipped with hygrograph; P, pilot balloon ascents made; R, radiosonde ascents made; W, radiowind ascents made. Number adjacent to stations, e.g. 666, is international station index number.

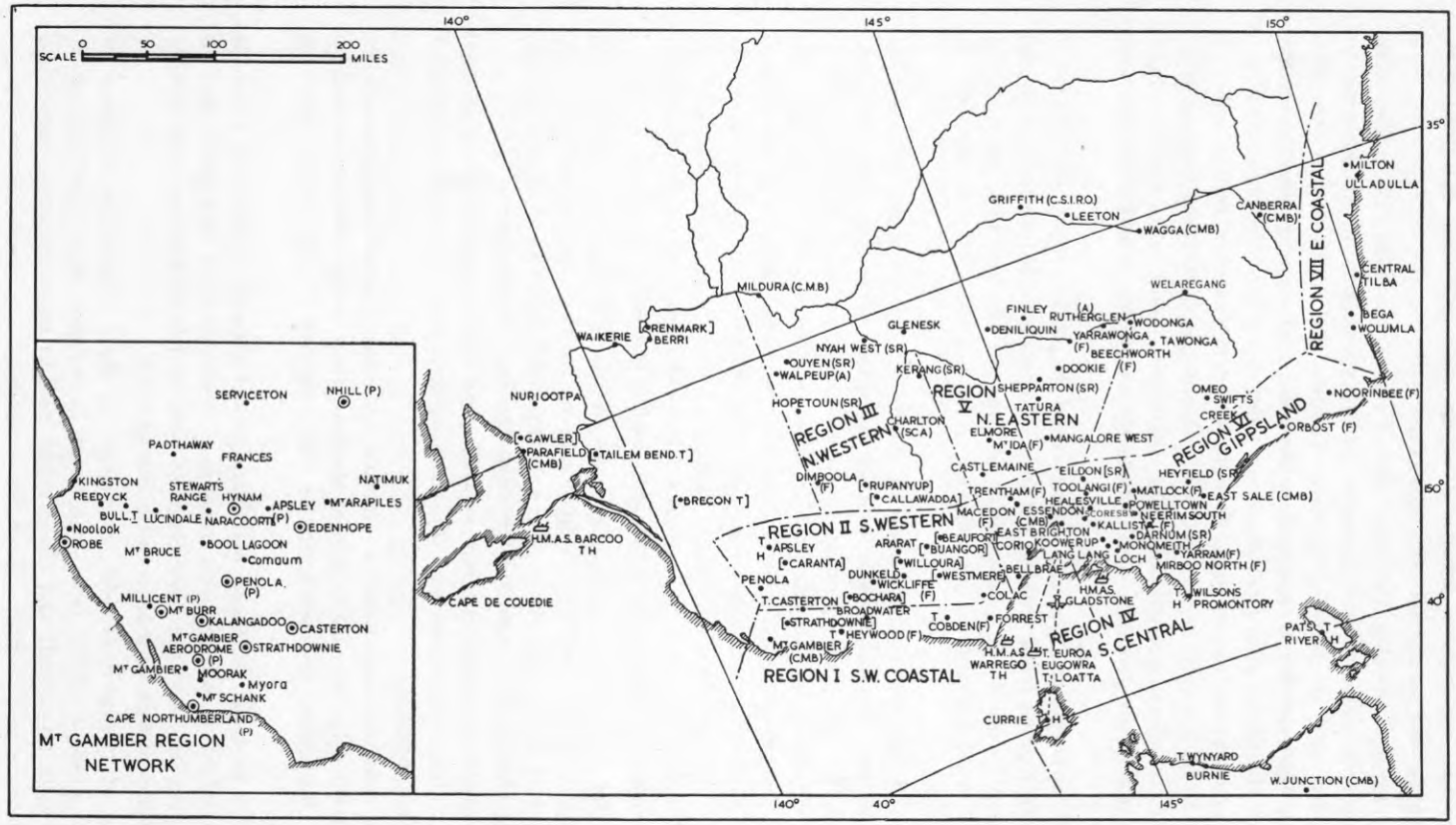

Fig. 12.—Supplementary Network.—Questionnaire stations and supplementary autographic records (T, thermograph; H, hygrograph). Letters in brackets denote cooperating authority as follows: F, Forests Commission of Victoria; SR, State Rivers and Water Supply Commission; A, Department of Agriculture; SCA, Soil Conservation Authority; LHS, Commonwealth Lighthouse Service; CMB, Commonwealth Bureau of Meteorology. Stations denoted thus [● Caranta] operated during Mt. Gambier campaign only.

Mt. Gambier Network.—○ Major Stations: equipped *at least* with wind-direction recorder, thermograph, hygrograph, and barograph. ● Minor Stations (less equipment): all except Padthaway, Mt. Arapiles, and Naracoorte have at least wind-direction recorder and thermograph. Stations not in capitals are forestry stations without autographic records. (P) Pilot balloon ascents made.

local thunderstorms, sea-breezes, katabatic winds, etc., and also the possibility of changes being missed owing to local masking.

At a few stations, notably Canberra and Western Junction (Tas.), the wind direction gave no clear indication of passages, probably owing to the masking action of local orography, and in parts of western Victoria and south-east South Australia there was a tendency for backing before the passage of a change-line, associated presumably with the formation of an afternoon "heat low" over the region and also possibly with penetrating sea-breezes though the temperatures rarely fell. A particular point to be borne in mind when using thermograph charts is that an overnight change, by disturbing ground inversion conditions, might bring about a slight rise in temperature at the ground. This was fairly frequently found to be the case at Mt. Gambier.

Additional approximate passage times could be obtained by the study of 3-hourly synoptic reports from Bureau stations. In using such information it was necessary to keep in mind the peculiarities of some of the stations, such as the tendency for the wind backing at Cape Otway to be delayed after the temperature fall.

It was found that the consideration of events in time at particular stations, using autographic records and serially plotted synoptic observations or "meteorograms", followed by the drawing of an isochrone chart for each separate change, was necessary for accurate analysis on the time and space scale involved. The isochrone charts were essential to provide continuity, bridging both the physical gaps between observing stations and the time gaps brought about by the lack of reports outside normal working hours from many synoptic reporting stations. The absence of reports at 1800 and 2100 hr was especially felt, as the intensity of cloudiness and precipitation frequently reaches a maximum during the evening.

Often partial or negative information was useful. The 3-hourly reports from synoptic stations could be used only to give a range for the time of passage in the absence of a special discon report; or, for a station with incomplete time coverage, evidence that a change had passed later than the last observation.

Synoptic charts at standard hours were of some help, especially those at 0900 and 1500 hr local time, since there is on these a fairly dense network of reports of wind direction and temperature.

When the changes were weak or masked by stray diurnal temperatures (or both), as was frequently the case at inland stations, they could often be located by comparison of maximum temperatures or temperatures at the same time on successive days.

Care had to be taken to avoid attributing local showers to steps of a double change when evaluating autographic records. Variations of dew-point and of equivalent temperature, and the persistence of wind and temperatures, were mostly the best indications to distinguish synoptic change-lines.

Continuity of change-lines.—On occasions, marked differences in speed of movement were evident either from one point to another along the line, or at different times as it advanced, and these could lead to large apparent distortions unless their existence was verified. Such discontinuities, i.e. breaks in the change-

lines or abrupt acceleration or deceleration, occurred chiefly near the border between Victoria and South Australia, but also in eastern Bass Strait.

Effect of orography on movement.—Autographic records made available by the Snowy Mountains Hydro-Electric Authority made possible a reasonably accurate tracing of the change-lines over the mountains of south-east New South Wales. Most changes were found to experience a strong distortion in the area, penetrating far along the coast before their effects were felt in the mountains, and this applied in particular to the first steps of double changes. In the eastern parts of the mountains the wind shift is to south-east, instead of south-west as over Victoria. Some changes did not penetrate the high parts of the mountains at all. A similar, but less pronounced, distorting action was sometimes noticed with the mountains of central and western Victoria—although it was generally difficult to trace the passages across north Tasmania, owing to a tendency for small temperature falls and confused wind changes, it was evident that the disturbances often move along the coast of south-east Victoria before traversing north Tasmania, so that a NNE.–SSW. orientation across Bass Strait is commonly found, in contrast with the dominant NNW.–SSE. or NW.–SE. orientation observed elsewhere.

Action of the highlands on either side is the more likely explanation. It may be noted here that analysis sometimes revealed the occurrence of more than two steps. The additional step usually affected only a limited area and usually followed the main steps. The most frequent observation of such multiple changes was in the Bass Strait region where a third step was commonly associated with a deepening depression south of Tasmania.

Appendix II

SOURCES OF DATA

This appendix lists the Government departments and authorities that provided data from records, or whose officers cooperated by providing questionnaire returns, and also the private citizens who assisted in the observations. The list given here covers those whose observations are utilized in Part I (the present publication); others, such as those assisting in the field work in South Australia, will be acknowledged in Part II.

Commonwealth Government.—

C.S.I.R.O. (Murrumbidgee Irrigation Research Station, Griffith, N.S.W., and Regional Pastoral Laboratory, Deniliquin, N.S.W.)
Department of the Navy
Lighthouse Service
Snowy Mountains Hydro-Electric Authority
Postmaster-General's Department

Victorian Government.—

Forestry Commission
State Rivers and Water Supply Commission
Horticultural Section, Department of Agriculture

Other Observers.—

Mr. J. Anderson, Postmaster, Currie, King Island
Mr. E. R. Barratt, Waikerie, S. Aust.
Mr. A. J. Bax, Ulladulla, N.S.W.
Mr. H. N. Brown, Penola, S. Aust.
Mr. E. C. Blackburn, Milton, N.S.W.
Mr. T. D. Dowling, Glenesk, N.S.W.
Mr. R. Dart, Casterton, Vic.
Mr. C. Einsiedel, Monomeith, Vic.
Mr. P. H. Ferris, Penola, S. Aust.
Messrs. G. E. Fletcher and R. J. R. Walker, Officers-in-Charge, Department of Civil Aviation Aerodrome, Flinders Island.
The General Superintendent, Associated Pulp and Paper Mills, Burnie, Tas.
Mr. A. E. Glisson, Castlemaine, Vic.
Mrs. E. D. Hart, Finley, N.S.W.
Mr. W. B. Harris, Manager, Horticultural Station, Berri, S. Aust.
Mr. L. J. Hainsworth, Officer-in-Charge, Potato Research Station, Healesville, Vic.
Mr. C. H. Harkness, Principal, Dookie Agricultural College, Vic.
Mr. N. V. Hardy, Apsley, Vic.
Mr. G. H. James, Elmore, Vic.
Mr. J. P. Jennings, Manager, Horticultural Station, Nuriootpa, S. Aust.
Mr. B. E. Jephcott, Welaregang, N.S.W.
Mr. E. Johnston, Wolumba, N.S.W.
Mr. L. G. Laing, Corio, Vic.
Miss L. Louden, Tawonga, Vic.
Mr. N. Miller, Officer-in-Charge, Department of Civil Aviation Aerodrome, Wynyard, Tas.
Mr. S. Moyes, Loch, Vic.
Mr. B. M. Moss, Colac, Vic.
Mr. S. J. McIntosh, Wodonga, Vic.
Mr. P. J. McAuliffe, Broadwater, Vic.
The Postmaster, Omeo, Vic.
Mr. L. V. Pritchard, Postmaster, Leeton, N.S.W.
Mrs. J. F. Taylor, Central Tilba, N.S.W.
Mr. W. J. Webber, East Brighton, Vic.
Mr. P. R. Wrathall, Bega, N.S.W.
Mrs. D. B. Williams, Bellbrae, Vic.
The Master, A.M.V. *Loatta*.
The Master, M.V. *Euroa*.
The Master, M.V. *Eugowra*.